Adaptive receiver-based preamble-sampling mac protocol for low power and lossy wireless sensor networks

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ADAPTIVE RECEIVER-BASED PREAMBLE-SAMPLING MAC PROTOCOL FOR LOW POWER AND LOSSY WIRELESS SENSOR NETWORKS

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Dedicated to Mom, Dad, Sara and Selina

Abstract

Low-power and lossy Wireless Sensor Networks (WSNs) consist of a large number of resource constrained sensors nodes communicating over a lossy wireless channel. The key design criteria in low-power and lossy WSNs are energy-efficiency and reliability of data delivery. Sensors are low-cost, battery-powered electronic devices with limited computational and communication capabilities. They are prone to failure due to energy depletion, hardware malfunction, etc. This causes links to create or break and hence the connectivity graph to change. In addition, path loss, shadowing and multipath fading make the links unstable. The main energy savings in sensors can be achieved by keeping the radio in sleep mode for maximum possible duration. The Medium Access Control (MAC) protocol is responsible for controlling the status of the radio; its behaviour consequently affects the energy-efficiency of the sensors. In this work a set of energy-efficient and reliable communication mechanisms for low-power and lossy WSNs are proposed. It can also be applicable for Internet of Things (IoT) and Machine-to-Machine (M2M) systems. The contributions of this thesis are:

- We propose a Receiver-Based MAC (RB-MAC) which is a preamble-sampling protocol that dynamically *elects* the next receiver among potential neighbours, based on current channel conditions. The proposed scheme is resilient to lossy links, and hence reduces the number of retransmissions. We show by analysis, simulation, and practical implementation how it outperforms the state-of-the-art sender-based MAC protocols in terms of energy-efficiency, delay and reliability.
- We introduce two extensions of RB-MAC: adaptive preamble MAC (ap-MAC) and adaptive sampling MAC (as-MAC) protocols. We demonstrate through analytical and simulation that the proposed extensions improve the end-to-end energy efficiency and delay while maintaining comparable reliability of data delivery.
- We apply RB-MAC to IETF ROLL's RPL routing protocol [RFC6550] to study the multi-hop performance of RB-MAC. The analytical and simulation-based results show significant improvement in energy-efficiency, delay and reliability against sender-based MAC.

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Acronyms

3GPP	3rd Generation Partnership Project
ACK	Acknowledgment
ACM	Association for Computing Machinery
AODV	Ad hoc On demand Distance Vector routing protocol
AMI	Advanced Metering Infrastructure
ap-MAC	adaptive preamble MAC
as-MAC	adaptive check interval MAC
BER	Bit Error Ratio
BFD	Bidirectional Forwarding Detection
BMAC	Berkeley MAC
CCA	Clear Channel Assessment
CDMA	Code Division Multiple Access
CI	preamble sampling Check Interval
CRAHN	Cognitive Radio Ad Hoc Network
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
CPU	Central Processing Unit
CW	Contention Window
DAG	Directed Acyclic Graph
DAO	Destination Advertisement Object
DATA	Data Packet
DIO	DODAG Information Object
DODAG	Destination Oriented DAG

DSR	Dynamic Source Routing
DYMO	Dynamic MANET On-demand routing protocol
ETSI	European Telecommunications Standards Institute
ETX	Expected Transmission
FDMA	Frequency Division Multiple Access
FFD	Full Function Device (FFD)
GCC	GNU Compiler Collection
GNU	Gnu is Not Unix
GPIO	General Purpose Input / Output
GPS	Global Positioning System
HART	Highway Addressable Remote Transducer
HVAC	Heating, Ventilation, and Air Conditioning
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IS-IS	Intermediate System to Intermediate System
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
LBR	Low power and lossy Border Router
LEACH	Low Energy Adaptive Clustering Hierarchy
LLC	Logical Link Control
LLN	Low-power and Lossy Networks
LPL	Low asynchronous Power Listening
LWIM	Low Power Wireless Integrated Microsensors
M2M	Machine-to-Machine

MAC	Medium Access Control
MCU	Microcontroller Unit
OLSR	Optimised Link State Routing
OSI	Open System Interconnection
OSPF	Open Shortest Path First
PER	Packet Error Rate
PLC	Powerline Communication
PMF	Probability Mass Function
PS-MAC	Preamble Sampling Medium Access Control
QoS	Quality-of-Service
RB-MAC	Receiver Based MAC
REQ	Request
RFC	Request-For-Comments
RFD	Reduced Function Device
RIP	Routing Information Protocol
ROLL	Routing Over Low-power Lossy links
RPL	Routing Protocol for Low-Power and Lossy Networks
RTS	Request To Send
RX	Reception
SB-MAC	Sender-Based MAC
SDMA	Space Division Multiple Access
SIG	Special Interest Group of ACM (Association for Computing Machinery)
S-MAC	Sensor MAC
TBRPF	Topology Broadcast based on Reverse-Path Forwarding

TMAC	Timeout MAC
TDMA	Time Division Multiple Access
TSMP	Time Synchronized Mesh Protocol
TX	Transmission
WiFi	Wireless Fidelity
WiSeMAC	Wireless Sensor MAC
WLAN	Wireless Local Area Network
WOR	Wake On Radio
WSN	Wireless Sensor Network

Notations

d	data frame size in bits
$\mathrm{D_{ACK}}$	time duration of a ACK frame
D_{cca}	time duration of Clear-Channel-Assessment (CCA)
D_{CW}	time duration of Contention Window
D_{DATA}	time duration of payload (message)
D_{REQ}	time duration of preamble (consist of micro-frames)
D_{basic}	delay in one transmission
D_{Total}	total delay including retransmissions
E_{basic}	consumed energy in one transmission in RB-MAC
E'_{basic}	consumed energy in one transmission in 1-hopMAC
E_{Comp}	energy consumed in competing node
E_{MH}	Energy consumed in multi-hop communication
E_{REQ}	energy consumed during long preamble in transmitting node
E_{Rx}	consumed energy in receiver node
E_{Total}	total energy consumed by all sensor nodes within one-hop distance of sender
E_{Tx}	energy consumed in the transmitter
L_{pr}	preamble length
L'_{pr}	preamble length in ap-MAC
m	micro-frame size in bits
M	number of receivers in ap-MAC
n	number of retransmissions
N	number of neighbours (node degree) and number of receivers in RB-MAC

p	bit error probability
p_d	probability that a data frame is corrupted, $p_d = 1-(1-p)^d$
p_f	probability of failure of a single transmission
P_{listen}	consumed power in listening mode
p_m	probability that a micro-frame is corrupted, $p_m = 1-(1-p)^m$
P_r	power drained in receive mode
P_{Ret}	Probability of retransmission
P_{Rx}	consumed power in receiving mode
P_{sleep}	consumed power in sleep mode
P_t	power drained in transmit mode
P_{Tx}	consumed power in transmitting mode
P_s	power drained in sampling mode
r_d	data duration in the unit of $T_m, r_d = \left\lceil\frac{T_d}{T_m}\right\rceil$
r_{CW}	contention window interval
r_m	number of micro-frames transmitted in preamble, $r_m = \left\lceil\frac{L_{pr}}{T_m}\right\rceil$
r'_m	number of micro-frames transmitted in preamble in ap-MAC
τ	transition time from sleep mode to active mode
T_{CS}	carrier sense duration
T_{CTS}	clear to send duration
T_{CW}	contention window duration
T_d	transmission time of one data packet
T_m	transmission time of one micro-frame
V	number of receivers in as-MAC

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"A great piece of art is composed not just of what is in the final piece, but equally important, what is not. It is the discipline to discard what does not fit-to cut out what might have already cost days or even years of effort, that distinguishes the truly exceptional artist and marks the ideal piece of work, be it a symphony, a novel, a painting, a company or, most important of all, a life."

Jim Collins, 2003, the author of Good to Great and co-author of Built to Last.

1. Introduction

1.1. Low-power and Lossy Wireless Sensor Networks

Advances in semiconductor technologies have followed Moore's law and enabled mass production of low-cost, low-power and small-size electronic devices with sensing, processing and wireless communication capabilities. **Wireless Sensor Networks (WSNs)** have received a great amount of attention in academia and industry. WSNs consist of a large number of resource-constrained sensors, densely deployed across a geographical area to report a phenomenon (e.g. event, temperature, humidity) to a collection point called sink. Wireless sensor nodes maybe powered by small internal batteries and tend to operate for few years without human intervention or the need to replace batteries. The short transmission range imposed by extremely restricted energy budget makes it impossible for sensors to communicate directly with the sink. Therefore, sensor nodes need multi-hop paths using other intermediate sensor nodes in the network as relays to forward their sensed data to the sink. Hence in addition to generating data, each individual sensor acts as a router. Consequently, dense deployment of sensors is essential to ensure network connectivity. Figure **1-1** [EXA12] shows the taxonomy of wireless technologies based on data rate and range performance. Sensor networks have been deployed for decades in a variety of scenarios in public and private sectors, such as environmental monitoring, healthcare, security and surveillance, home intelligence, industrial process control, disaster monitoring, etc. **Table 1-1** shows the important events in the history of WSN technology [Doh12].

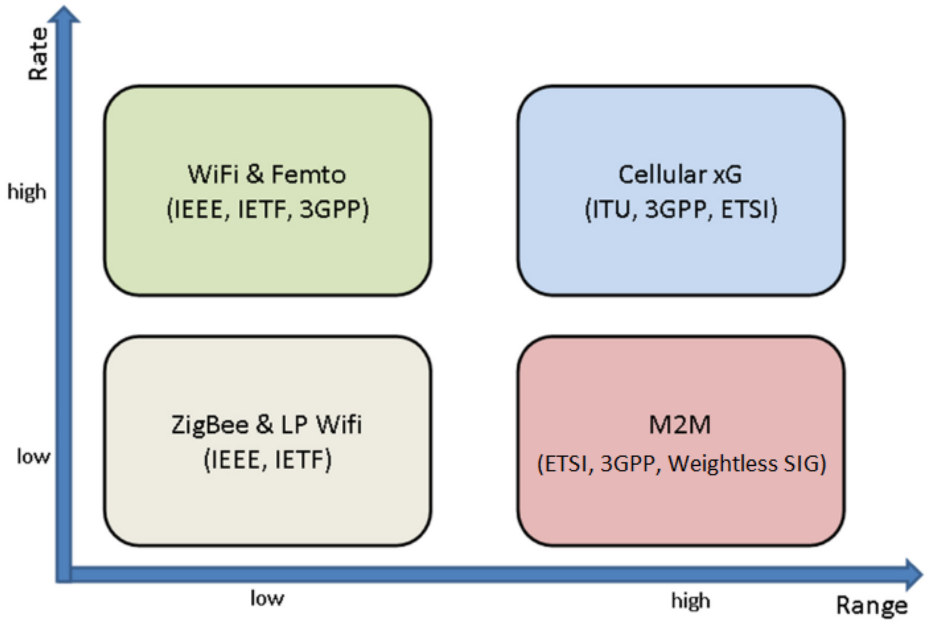

Figure 1-1: Taxonomy of Wireless Technologies

Low-power and Lossy networks (LLNs) [RFC6550] are composed of a large number of resource-constrained devices in energy, memory and computational capabilities that are connected via wireline links or wireless channels. A range of different technologies are used, such as Zigbee, Bluetooth, Low Power WiFi, wired or other low power PLC (Power line Communication) links. Internet Engineering Task Force (IETF) Over Low-power Lossy (ROLL)'s Working Group has defined the characteristics of LLN as follows [CHA08]:

- LLN may potentially be comprised of thousands of low-power nodes.
- Links in LLN are usually unstable
- LLN devices can operate with very little bound on state information
- LLN needs to optimise for saving energy.
- Typical traffic patterns are not just unicast flows (can be point-to-multipoint as well in some cases).
- The traffic must be carried over links that can forward only small and restricted frames

These specific properties cause LLNs to have specific routing requirements which are discussed at length in Section 3.2. Some use cases of LLNs are industrial monitoring, building automation, connected homes, healthcare, environmental monitoring, urban sensor networks, and asset tracking [CHA08]. More use cases are presented in section 1.2.

Table 1-1 Historic Events in WSN

Year	**Event**
1967	REMBASS Remotely Monitored Battlefield Sensor System
1978	Distributed Sensor Networks for Aircraft Detection Lincoln Labs – Lacoss
1992	RAND Workshop – Future Technology Driven Revolutions in Military Conflict. Concepts behind Smart Dust emerge.
1993-1996	DARPA ISAT studies – many WSN ideas and applications discussed. Deborah Estrin leads one of the studies.
1994	LWIM – Low Power Wireless Integrated Microsensors – UCLA, Bill Kaiser
1997	Smart Dust proposal written – UC Berkeley, Kris Pister
1998	Seth Hollar makes wireless mouse collars
1999	Endeavour project proposed by Randy Kats, David Culler PicoRadio project started by Jan Rabaey
2000	Crossbow begins selling “Berkeley motes”
2001	Multiple demos proving viability
2002	Dust, Ember, Millennial, Scesicast founded
2003	IEEE802.15.4 standard published Moteive (now Sentilla) founded
2004	Zigbee 1.0 standard ratified TSMP 1.1 (Time Synchronized Mesh Protocol) shipping by Dust Network
2005	Arch Rock founded
2006	Zigbee 2006 standard ratified
2007	Wireless HART standard ratified RFC4944 published (Transmission of IPv6 Packets over IEEE 802.15.4 Networks)
2008-2009	IETF workgroup Routing Over Low-power Lossy links (ROLL) created IEEE 802.15.4e workgroup created
2010	IEEE 802.15.4e’s MAC protocol ratified IETF 6lowPAN’s RFC4944 updated IETF’s RPL routing protocol ratified
2011	Inaugural Standards SIG (S-SIG) for Weightless retrieved at Moller Centre in Cambridge, UK
2012	Weightless SIG revealed to the public RFC6550 published (RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks)
2013	Formal Weightless v1.0 standard published
2014	The IEEE 802.11ah working group (ultra low-power WiFi) will occur in November 2014

Low-power and lossy WSNs – the focus of our work – consist of a large number of resource constrained sensors nodes communicating over a lossy wireless channel. The key design criteria in communication protocols for low-power and lossy WSNs are energy-efficiency and reliability of data delivery. Sensors are low-cost, battery-powered electronic devices with limited computational and communication capabilities. They are prone to failure due to energy depletion, hardware malfunction, damage from the environment, etc. In some scenarios sensors may be inserted to the network to improve connectivity. Sensor nodes may move to new positions out of range of their previous neighbours, triggering the creation of new communication links. In environmental energy-harvesting sensor networks, dynamicity of the network is even higher because a sensor node can join or leave the network depending upon the availability of energy source (e.g. solar-powered sensor nodes may run out of power over continuous dark cloudy days, a change in direction of solar panel; or the solar panel is covered by dust and dirt) [Akh11]. Conditions such as these cause links to be created or broken and hence the connectivity graph formed by the networked wireless nodes become highly dynamic. Therefore, reliability of data delivery is important in designing communications protocols for low-power and lossy WSNs. In addition, wireless links are unstable by nature, and their reliability varies over time, thus high error rate links are commonplace. This is due to path loss, shadowing and multipath fading which cause links to be intermittent and thereby the connectivity graph to change. A lossy link in not only characterised by a high Bit Error Rate (BER) but also the long inaccessibility period [Gad12], which considerably impact the communications protocol design. **Figure 1-2** shows samples from a realistic analytical link loss model [Sea04]. Retransmission count has been used in most protocols to maintain a satisfactory level of reliable data delivery in LLNs. However, retransmissions consumes energy and also increase transmission delay. Number of retransmission can be used to determine the lossyness of the link, and in low-traffic network it is difficult to determine whether or not the link should be considered as down [Vas10].

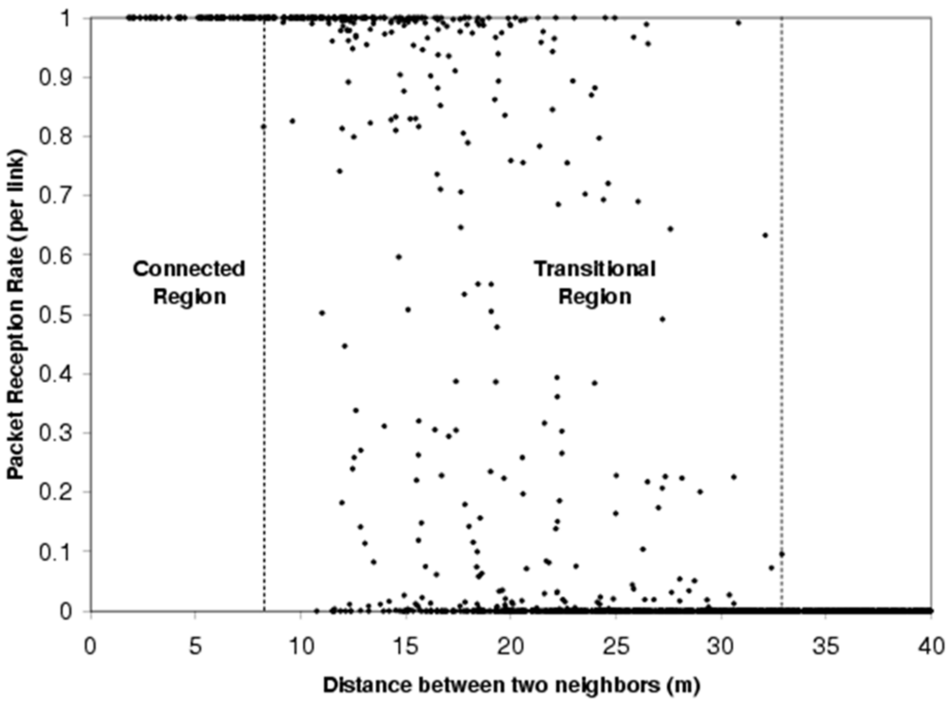

Figure 1-2 Samples from a realistic analytical link loss model [Sea04]

Based on recent studies and experiments (**Figure 2-1**), it can be deduced that the main energy savings in a wireless sensor node can be achieved by keeping the radio in sleep mode for a maximum possible duration. The Medium Access Control (MAC) protocol is responsible for controlling the status of the radio; its behaviour consequently affects the energy-efficiency of the sensors. Putting the sensor node in sleep mode, however, would mean that the nodes would require more complex arrangements to communicate. As a result, there is a trade-off between node's energy-efficiency and availability for communication.

In this work, a set of energy-efficient and reliable communication mechanisms for low-power and lossy WSNs are proposed. This set can also be suitable for low-traffic Internet of Things (IoT) and Machine-to-Machine (M2M) communications systems. We propose Receiver Based MAC (RB-MAC), a preamble-sampling MAC protocol, which dynamically elects the next-hop among a number of potential neighbours for relaying data traffic, based on current channel conditions. We proved that the proposed scheme is resilient to lossy links by nature and thus reduces the number of retransmissions making the packet delivery more energy-efficient. We show by analysis, simulation runs and practical implementation of how it outperforms the state-of-the-art sender-based preamble-sampling MAC protocols.

RB-MAC is specifically designed for low-power and lossy WSNs that generate low-traffic. Its design is aimed at guaranteeing robustness against network dynamicity and interferences, scalability in network size and low latency with low power consumption. RB-MAC can be applied to any gradient based routing protocols including geographic routing protocols RPL [RFC6550] of IETF's ROLL (Routing Protocol for Low-Power and Lossy Networks) Working Group.

1.2. Applications

Wireless sensors have been used to detect or monitor a variety of physical phenomena such as [Lib13]:

- **Smart Cities:** smart parking, structural health, noise urban map, smart phone detection, electromagnetic field level, traffic congestion, smart lighting, waste management, smart roads
- **Smart Environment:** forest fire detection, air pollution, snow level monitoring, landslide and avalanche prevention, earthquake early detection
- **Smart Water:** water quality, water leakages river floods
- **Smart Metering:** smart grid, tank level, photovoltaic installations, water flow, silos stock calculation
- **Security & Emergencies: p**erimeter access control, liquid presence, radiation levels, explosive and hazardous gases
- **Retail:** supply chain control, NFC payment, intelligent shopping applications, smart product management
- **Logistics:** quality of shipment conditions, item location, fleet tracking
- **Industrial Control:** M2M applications, indoor air quality, temperature monitoring, Ozone presence, indoor location, vehicle auto-diagnosis

- **Smart Agriculture:** wine quality enhancing, green houses, golf courses, compost
- **Smart Animal Farming:** animal tracking, toxic gas levels
- **Home Automation:** energy and water use, remote control appliances, intrusion detection systems, art and goods preservation
- **e-Heath:** fall detection, medical fridges, sportsmen care, patients surveillance, ultraviolet radiation

Recently many multi-vendor equipment and hardware platforms for WSN have been designed, developed and produced. With no common platform available, different companies tend to use their own devices and platforms. The following diagram illustrates some of the main providers [Doh12] in this field. The interoperability of different platforms is one of the main challenges that prevent WSN from mass deployment and it seems the success of WSN to a great extent depends on the success of recent standardisation activities.

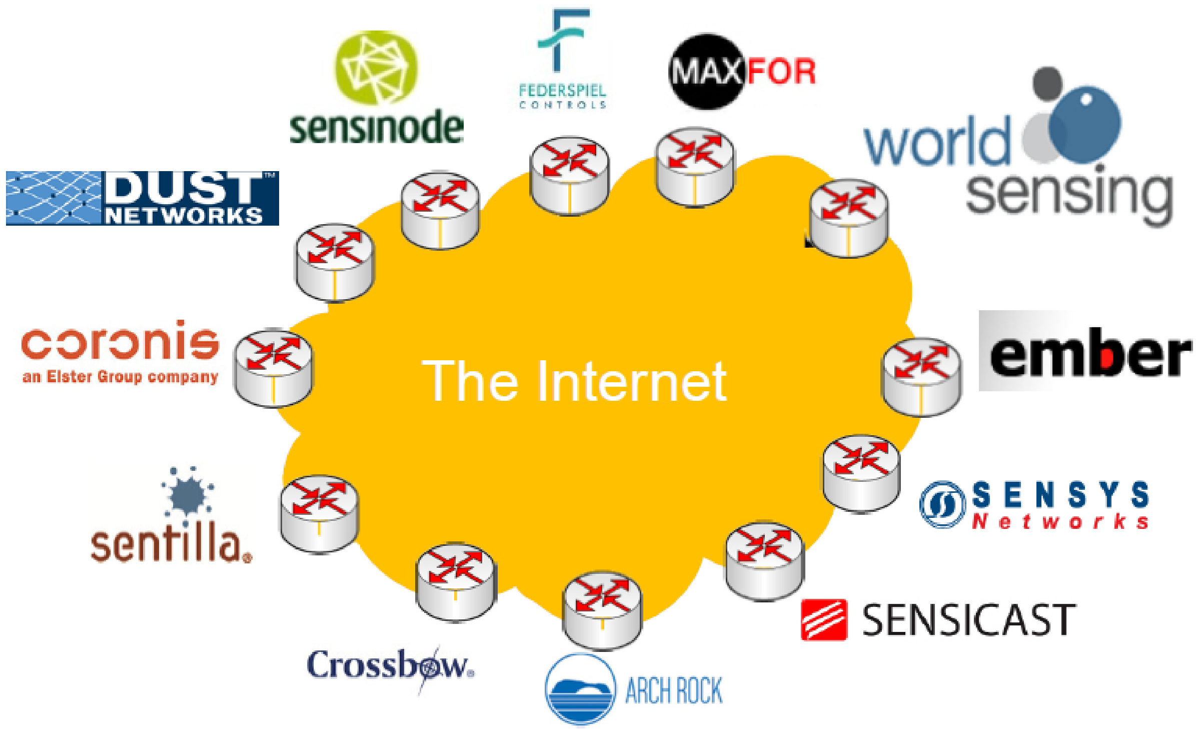

Figure 1-3 Providers of Wireless Sensor Platforms

1.3. Standards

Standardisation organisations involved in WSNs are as follows:

- IEEE (Institute of Electrical and Electronics Engineers) which typically standardises the physical and link layer (MAC) solutions (**Figure 1-4**). IEEE standards applicable to WSNs are: IEEE802.15.4 (technology used by ZigBee and IETF 6LowPan), IEEE 802.15.1 (technology used by Bluetooth/WiBree), IEEE 802.11x (technology used by WiFi), and IEEE 802.11ah.
- IETF (Internet Engineering Task Force) usually standardise routing and networking solutions (**Figure 1-4)**. Working groups involved in WSNs are 6LoWPAN (with focus on IPv6 connectivity between WSNs and the Internet) and ROLL (focusing on routing over low-power and lossy networks).
- ETSI (European Telecommunications Standards Institute) provides complete machine-to-machine solutions [ETS13]: Other component-level standards already exist that address various radio interfaces, different meshed or routed networking choices, or offer a choice of identity schemes and each is optimised for a particular application scenario and therefore there is a degree of fragmentation. ETSI aims to bring all these pieces together, and identify the standardization gaps which exist.
- oneM2M is globalised M2M solution and formally launched on 24th of July 2012 to develop technical specifications which address the need for a common M2M service layer that can be readily embedded within various hardware and software, and relied upon to connect the myriad of devices in the field with M2M application servers worldwide.
- Weightless is an wireless technology standard for M2M traffic exchanging between a base station and thousands of M2M devices using TV white Space spectrum (frequency channels intended for TV broadcasting but currently unoccupied) with high levels of security.

Other Forums and Associations involved in WSNs are:

- ZigBee Alliance was created to provide low-power and open global wireless networking standards focused on monitoring, control and sensor applications. It defines specific layers of protocol stack on top of PHY and MAC provided by IEEE 802.15.4.
- IEEE 802.15.4e adopts channel hopping strategy to improve support for the industrial applications, robustness against external interference and multipath fading
- WiBree (ultra low power communication based on Bluetooth technology), avenis OSA (from Coronis Systems, focuses on metering and urban monitoring),
- WirelessHART (an extension of Highway Addressable Remote Transducer. HART, dominant wireless sensor technology in automation and industrial control applications that require real-time support),
- The ISA SP100.11a standard developed by the Systems and Automation Society (ISA) with focus on process and factory automation,
- The Wireless Industrial Networking Alliance (WINA) attempts to increase industrial efficiency by using WSN technologies,
- Dash7 alliance (an open source protocol operates in the 433 MHz unlicensed ISM band)

Figure 1-4 and **Figure 1-5** illustrate some standardisation bodies and forums in WSN.

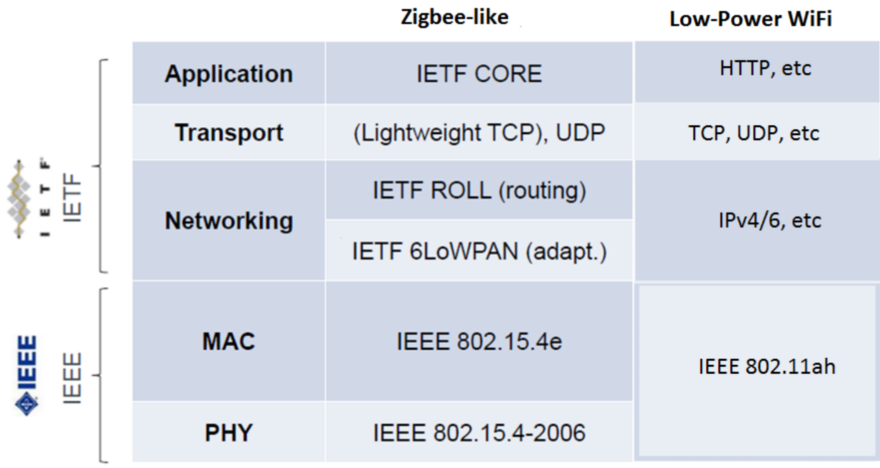

Figure 1-4 IEEE and IETF standards in Zigbee and Low-Power WiFi [Doh12]

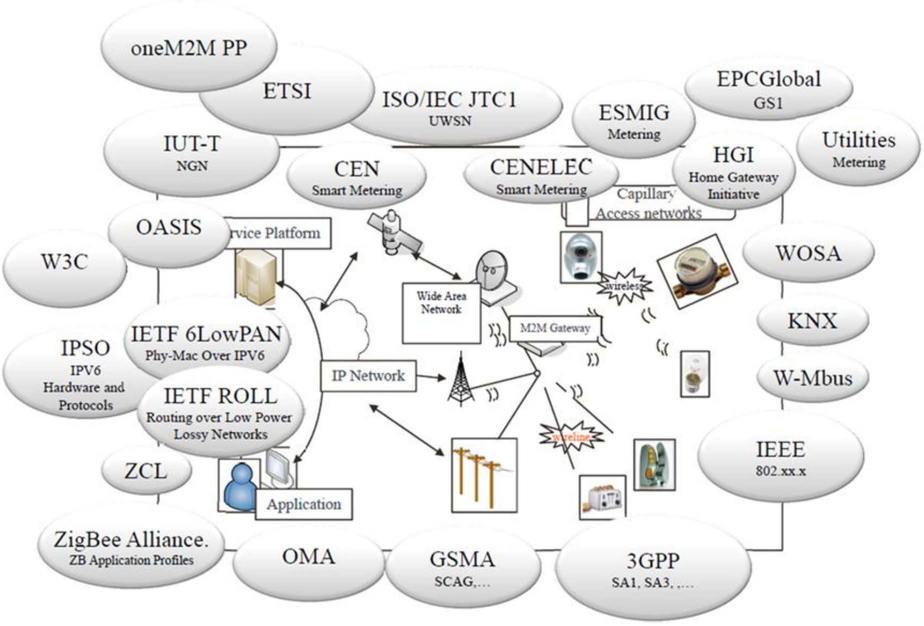

Figure 1-5 Different standardisation bodies related to WSN and M2M [Doh12]

1.4. Contributions and Thesis Organization

The nine chapters of this thesis are divided in two parts: background study and contributions. State-of-the-art in MAC and routing protocols are presented in Chapters 2 and 3. The contribution part contains our proposals for enhancing the performance of low-power and lossy WSNs.

In Chapter 2, we present an overview of MAC protocols in WSNs by introducing the challenges of MAC in WSNs, exploring the characteristics of different classes of MAC protocols, benefits and drawbacks of different mechanisms used, the existing standards and finally discuss the open issues.

Chapter 3 focuses on RPL: Routing Protocol for Low power and Lossy Networks, including protocol overview, design objectives, network model and other main features and specifications.

Chapter 4 provides the details about assumptions, models and targeted applications used in this thesis. Challenges and solutions in WSN are highly application-dependent and scenario-based. We describe the low-power and lossy WSN application scenario, its constraints and challenges. We later present the especial requirements of communications protocols.

In Chapter 5, we propose Receiver-Based MAC (RB-MAC) which is a preamble-sampling protocol that dynamically *elects* the next receiver among potential neighbours, based on current channel conditions. The proposed scheme is resilient to lossy links by nature, and hence reduces the number of retransmissions. We show by fairly simple analysis and numerical results how it outperforms the state-of-the-art sender-based MAC protocols in terms of energy-efficiency, delay and reliability.

In Chapter 6, we introduce two extensions of RB-MAC: adaptive preamble (ap-MAC) and adaptive sampling (as-MAC) protocols. We demonstrate through detailed analysis and simulation that the proposed RB-MAC and the extensions improve energy efficiency and latency while maintaining comparable reliability.

In Chapter 7, we apply RB-MAC to IETF's RPL routing protocol to study the multi-hop performance of RB-MAC. The analytical and simulation-based results show significant improvement in energy-efficiency, delay and reliability against sender-based MAC. The main objective is to integrate RB-MAC and RPL routing protocol capable of achieving a good trade-off between energy-efficiency and reliability.

In Chapter 8, the practical implementation of RB-MAC is discussed. We investigate the performance of the RB-MAC protocol in terms of transmission delay, and energy efficiency by using real-world implementation. To implement RB-MAC, we used the Configurable MAC (C-MAC) [Ste10] framework, which allowed us to evaluate and compare protocol performance by experimenting on real sensor nodes.

Finally, we conclude this dissertation and present future research directions.

The publications related to the contributions of the thesis are as follows:

1. Adnan Aijaz, Shuyu Ping, Mohammad Reza Akhavan and Hamid Aghvami CRB-MAC: A Receiver-based MAC Protocol for Cognitive Radio Equipped Smart Grid Sensor Networks, IEEE Sensor Journals, 2014.
2. Mohammad Reza Akhavan, Adnan Aijaz, Sabrieh Choobkar, and A. Hamid Aghvami, On the Multi-hop Performance of Receiver Based MAC Protocol in RPL based Low Power and Lossy Wireless Sensor Networks, IET Wireless Sensor System, 2014.
3. Mohammad Reza Akhavan, Sabrieh Choobkar, Adnan Aijaz, and A. Hamid Aghvami, Adaptive Preamble Sampling Techniques for Receiver Based MAC Protocols in Lossy Wireless Sensor Networks, IET Wireless Sensor Systems, 2014.
4. Rodrigo Vieira Steiner, Mohammad Reza Akhavan, Antônio A. Fröhlich, and A. Hamid Aghvami, Performance Evaluation of Receiver Based MAC Using Configurable Framework in WSNs, IEEE Wireless Communications and Networking Conference (WCNC 2013), Shanghai, China, April 2013.
5. Mohammad Reza Akhavan, Thomas Watteyne, and A. Hamid Aghvami, Enhancing the Performance of RPL by Using A Receiver-Based MAC Protocol in Lossy WSNs, The 18th International Conference on Telecommunications (ICT 2011), Ayia Napa, Cyprus, May 2011.
6. Mohammad Reza Akhavan, Mona Ghassemian, and A. Hamid Aghvami, EOR: An Energy-Aware Opportunistic Routing in Heterogeneous Wireless Sensor Networks, Ubiquitous Computing at a Crossroads Workshop, Imperial College London, UK, January 2009.

2. Medium Access Control Protocols

2.1. Introduction

Wireless communications are broadcast in nature and transmitted data over a wireless link can be received by several receivers that are within communication radio range of the transmitter. In this case, multiple transmissions of the nodes may overlap and cause interference and packet collision. Therefore, the main role of Medium Access Control (MAC) is to coordinate access of the nodes to the shared wireless medium by resolving the contention and minimising collision among competing nodes.

The MAC protocol (and LLC) are sublayers of the OSI's Data Link layer located just above the physical layer (PHY) and below the network layer. Under the influence of the physical layer, it has a huge impact over routing protocols in the network layer.

This chapter presents an overview of MAC protocols in WSNs. It introduces the challenges of MAC in WSNs and explores the characteristics of different classes of MAC protocols, the benefits and drawbacks of different mechanisms used and the existing standards.

2.2. Challenges for MAC

As stated in the previous chapter, the main characteristics of WSNs are resource constraint in terms of power and hardware, multi-hop communications, dynamic topology, and lossy channel. MAC protocols in WSNs are facing dissimilar challenges and therefore performance metrics and Quality-of-Service (QoS) need to be redefined. This section highlights the major challenges that face the MAC layer.

The major objectives in designing MAC protocols in traditional wireless networks are: increasing throughput, decreasing delay and sometimes offering fairness among users. However, in WSN delay and throughput are more application-dependent parameters. Fairness in WSN is not an issue since in most cases sensor nodes are not contending with each other, but are collaborating for a common goal [Bac10]. Therefore, MAC protocols in traditional wireless networks are not appropriate for WSNs. In addition, in many WSN roll-outs, network topology is highly dynamic and channel is lossy. Therefore, MAC protocol in these types of networks needs to comply with reliability requirements (successful transmission rate).

2.2.1. Energy

In WSN the main concern is energy efficiency. This is due to the fact that sensor nodes are constrained in power. A wireless sensor node consumes energy for processing, sensing, and radio communications. **Figure 2-1** illustrates the energy consumption of typical wireless sensor node components including radio, microcontroller and sensor. Based on recent studies, the main energy savings in a sensor node can be achieved when its radio is switched off. In other words, a wireless sensor node needs to spend most of the time in sleep mode (radio circuitry switched off) and only awake when there is a need to transmit or receive a packet. However; in the majority of WSNs there is no central node (similar to Base Station in cellular networks) to coordinate communications - and in the distributed deployment, sensor nodes do not have this knowledge. Therefore, MAC protocols in WSNs should introduce a control overhead to coordinate communications between sensor nodes [Aky10].

The most prominent energy dissipation at the MAC layer derives from the followings [YeH02]:

- **Idle listening:** As sensor node is not aware when a packet will transmit, their radio continuously listen to the channel and consequently consumes energy. This called idle listening. According to [YeH04] idle listening is the main source of energy dissipation in receiving wireless sensor nodes.

  Collisions: Wireless sensor nodes are not able to transmit and sense the channel at the same time (half-duplex wireless channel). There are possibilities that two or more sensor nodes transmit packets target to the same receiver at the same time. In this case, data packets collide with each other and the receiver does not receive the corrupted packets. This requires retransmitting the same packet and spending more energy. Most MAC protocols use collision avoidance techniques to overcome this issue.

- **Overhearing:** Overhearing occurs when a sensor node wastes energy for receiving an irrelevant packet (a packet that is not destined to it).
- **Protocol Overhead:** All extra control frames in the protocols that have been used coordinate and regulate communications in the wireless channel are overheads. Protocol overhead consumes energy and needs to be minimised.

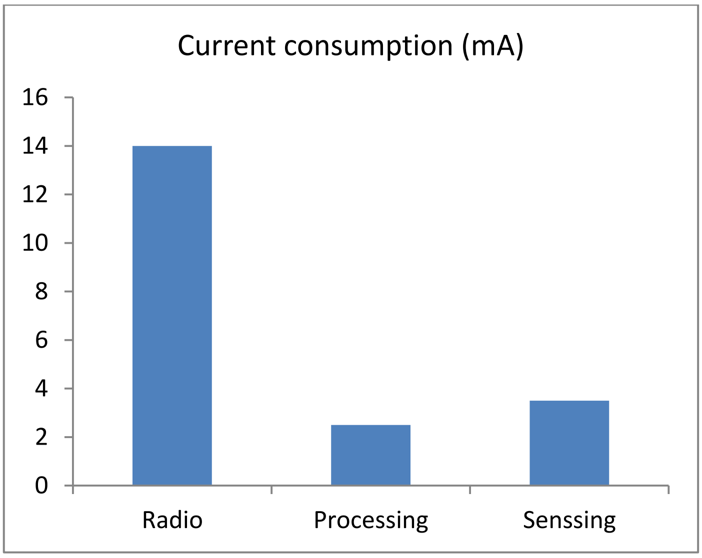

Figure 2-1 Energy consumption of typical wireless sensor components using CC2500 radio chip and MSP 430 MCU [Pla06]

To this end, MAC protocols in WSNs should be designed to coordinate communications between wireless sensor nodes in an energy-efficient and reliable way. This can be done by minimising idle listening, controlling overheads and collisions, controlling the status of the radio, and duty-cycling in the shared broadcast channel.

2.2.2. Node Density

Usually wireless sensor nodes are densely deployed in a geographic region. Higher node density provides better connectivity in WSNs without compromising increased transmission power [Aky10]. However, the probability of collision increases as a result of a high number of nodes within communication range of each other when they are contending for channel access. Therefore, the MAC protocol should be aware of the network and node density. Chapter 5 demonstrates how node density can improve performance of the proposed RB-MAC protocol in terms of reliability without jeopardising energy-efficiency.

2.2.3. Topology Change

Wireless sensor nodes maybe deployed in access controlled or hostile environments. In addition, low-power and low-cost sensor nodes are prone to theft, physical damage, and hardware failure. As a result, the connectivity graph and network topology can change. To this end, MAC protocols in WSN should be adaptive to the network dynamicity.

2.2.4. Traffic Pattern

Wireless sensor nodes in WSNs may generate different traffic patterns imposed by different applications. Any MAC protocol design should comply with traffic patterns; for example in monitoring applications where traffic is periodically generated, scheduled-based MAC protocol can be used. In event-based applications where traffic generated only during events, an access mechanism adaptive to the traffic is required [Aky10]. Moreover, MAC protocol should support Many-to-One (traffic flow from multiple source sensor nodes to the sink), One-to-One, and One-to-Many (queries and commends from the sink towards multiple source sensor nodes) traffic.

2.3. Classifications of MAC Protocols

Several MAC protocols in WSN have proposed different solutions and based on these different approaches, we can categorise MAC protocols into four main classes [Bac10]: Frame-based (scheduled), Contention-based, Preamble-sampling, and Hybrid Medium Access protocols.

2.3.1. Frame-based (scheduled) Protocols

In schedule-based or reservation-based protocols, the available network resource (e.g. time, frequency, etc.) is scheduled between the nodes in such a way that each node can use its own allocated resources to access the channel and communicate with other nodes without the need to be concerned about collision. Frame-based protocols are ideal for periodic and high-load traffic. Typical examples of this approach are TDMA, FDMA, CDMA, and SDMA. In the TDMA (Time Division Multiple Access) scheme, time is divided into frames. Single slot frame subdivided into a fixed number of time-slots. These time-slots assigned to nodes uniquely and each node has right to transmit during its time-slot periodically in every frame. In Frequency Division Multiple Access (FDMA), the frequency band is sliced into non-interfering frequency subchannels and assigned to nodes. FDMA is more complex than TDMA and needs frequency synchronisation. Code Division Multiple Access (CDMA) nodes use different codes that allow different signals to be sent at the same time/frequency. Finally, Space Division Multiple Access (SDMA) is based on directional antenna or multiple-antenna arrays.

The frame-based approach can offer finite and expected scheduling delays and increase throughput in networks with high data traffic. In addition, it can provide fairness among the competing nodes, although fairness is not a critical factor in a WSN. Nevertheless, these protocols are energy-efficient because of low collision probability and small overhead. Collisions can be well-managed in frame-based schemes.

In WSNs, the frame-based approach is not considered as a good technology solution because it requires tight synchronisation among nodes and knowledge of network topology (i.e. multi-hop awareness) which are not easily feasible in dynamic and unreliable WSNs. For instance, if a node (dis)appears, the allocated time-slot should be amended accordingly and this produces large overhead. In addition, strict synchronisation is a burden for scalability. SDMA requires complex signal processing techniques and cannot be considered a candidate technology for WSNs [Leh99].

In general, TDMA-based protocols follow common principles, where each node communicates according to a specific superframe structure [Aky10] as illustrated in **Figure**

2-2. The superframe consists of two main parts: reservation period and data period. Nodes use the reservation period to reserve time slots to communicate with other nodes. The data period contains several time slots that nodes use to transmit data. TDMA-based protocols are different in terms of slot allocation policy, and frame size. We review the representative reservation-based protocols in the following.

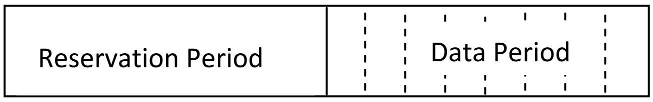

Figure 2-2: General frame structure for TDMA-based MAC protocol

LEACH (Low-energy Adaptive Clustering Hierarchy) [Hei00] is a TDMA-based MAC protocol consists of a clustering scheme and a simple routing protocol. LEACH divides sensor nodes into clusters with a clusterhead. Clusterheads set the schedule for member nodes in which each member has its own allocated slot to communicate with the cluster head. There is no peer-to-peer communications between member nodes in the cluster. Member nodes can only communicate with the clusterhead. Clusterheads aggregate the data from member nodes and directly transmit to the sink or other possible relaying nodes. Since the sink maybe located a long distance from the sensor networks, a clusterhead needs to spend a significant amount of energy to communicate with it directly [Kar05] (if multihop is not used). On the other hand, a clusterhead needs to keep its radio on in order to listen to all member nodes. These functions consume considerable energy causing the clusterhead to deplete very quickly. Consequently, there is a disconnection of the cluster from the rest of the WSN. To address this, LEACH has proposed a rotation plan for the role of clusterhead. Each member node in the cluster is eligible to be a clusterhead. The decision is made independently by each node based on the last time the node became a clusterhead. This rotation makes energy dissipation uniform across the network.

The important issue in LEACH protocol is choosing the optimal number of clusters. Based on the scenarios investigated in [Hei00, Hei02] this number is about 5% of total nodes *N*. If this optimum number is used, energy consumption of LEACH can be 7 to 8 times lower than when each node transmits its data directly to the sink, and about 4 to 8 times lower than multi-hop communications [Kar05]. **Figure 2-3** illustrates the organisation and operation of LEACH. In Setup phase, clusterheads are selected, formed, and clusters' common schedule is determined. Setup phase starts with process of choosing a random number by each sensor. The selected number is between 0 and 1 and id the number is less than a threshold the probability of becoming a clusterhead increases. Setup phase consists of three sub-phases: Advertisement phase, Cluster setup phase and Broadcast schedule. In advertisement phase, new clusterheads advertise themselves using CSMS to avoid advertisement packet collisions. In the second subphase, cluster members compete with CSMA and Broadcast schedule subphase, schedules are created. In Steady-state phase has been used for data communications between clusterhead and member nodes.

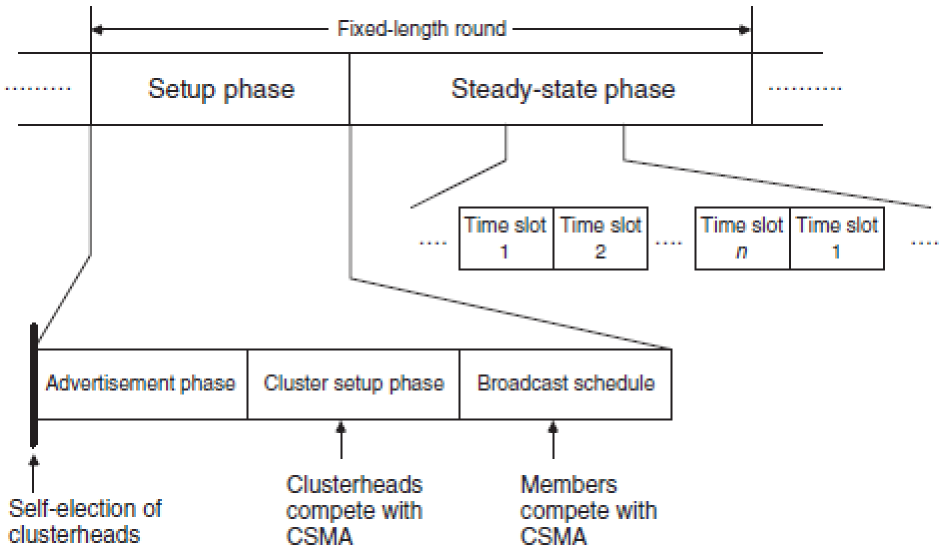

Figure 2-3: Organisation of LEACH rounds [Kar05]

The described LEACH protocol assumes that all sensor nodes can communicate directly with the sink when select as a clusterhead. This is not always feasible in WSN as it may cover a wide geographical area. As typical sensor nodes are low-power nodes with limited transmission range, even if they can transmit over a far distance their battery depletes quickly. This problem can be partly tackled by using multi-hop communications between clusterheads.

SMACS (Self-organising Medium Access Control for Sensor networks) is a distributed scheduling TDMA-based protocol proposed by Sohrabi et. al [Soh00]. Unlike LEACH, it uses a local scheduling in each sensor thus avoiding the shortcomings of transmitting data to the central clusterhead and slot allocation. SMACS define transmission and reception slots in two stages: neighbourhood discovery and channel assignment. In SMACS, if a neighbour is discovered, a channel will be assigned to it. Each link between two sensors nodes operate on a different channel, i.e. different frequencies are arbitrary selected to reduce collision. To discover a neighbour, a sensor node wakes up and listens over a period of time to receive request (invitation) packets. If it does not receive such a packet, it starts sending invitation packets requesting its neighbour nodes to establish a link. When a link between two nodes is established, they exchange few packets to assign transmit slot and receive slots. The established link is directional and all packets are transmitted from one sensor node (with transmit slots) to the other one (which has received slots). For bidirectional communications two such links between nodes are required. Sensor nodes sleep and wake up randomly to save energy.

SMACS is based on the following assumptions [Kar05]:

- The available spectrum is subdivided into different channels and each sensor node can tune its transceiver to a random one.
- Sensor nodes are mainly stationery and channel assignment is valid for fairly long time.

One of the advantages of SMACS is its simplicity of implementation. Since the neighbour discovery and slots assignments are done locally in a distributed fashion, there is no need to transmit the neighbourhood information to a central node (i.e. clusterhead) to process the global assignment. Therefore, SMACS is scalable; in particular, it supports multi-hop routing. However, some disadvantages are: low-degree network connectivity, difficulty in creating optimal routes, and the broadcast is not supported by defaults as it creates unicast communications. In addition, SMACS is not energy efficient especially in dense wireless sensor networks with low data traffic, as nodes are required to wake up more frequently to notice if there is a packet destined to them. The number of wake up slots is determined by node density.

TRAMA (Traffic-Adaptive Medium Access) [Raj03] is a collision-free scheduling MAC protocol in which the schedules are created on-demand and in a distributed fashion. TRAMA assumes that all sensor nodes are synchronised and divides time into *random access period* and *scheduled-access period*. A r*andom access period* followed by a *scheduled-access period* makes a cycle. The protocol consists of two stages: localised topology formation and schedules channel access. The schedules channel access is designed to tackle idle listening and overhearing in which each sensor node takes up only to transmit or receive. In this protocol, sensor nodes broadcast their two-hop neighbourhood information and schedule information with their neighbours. The schedule information is updated periodically according to the traffic rate or the packets currently in a sensor-node's queue.

TRAMA can be considered as a good MAC solution for resource-rich sensor nodes, as the complexity of the protocol demands substantial processing capabilities and memory, which are not found in a typical WSN. This is true in particular for dense networks, wherein a two-hop neighbourhood of a node tends to be large [Kar05]. Moreover, TRAMA assumes that all nodes are synchronised in the network. This also makes it a less attractive MAC solution for WSNs.

2.3.2. Contention-Based Protocols

In contrast to a reservation-based approach, in contention-based protocols resource allocation is done in an on-demand fashion. Therefore, they are more flexible with respect to changes in traffic pattern and node density. Moreover, they are robust against network dynamicity. In contention-based protocols, sensor nodes compete to transmit data in the same channel. However, in these protocols, increasing node density increases the probability of collisions. Collisions occur when two or more nodes try to send packets at the same time. Unlike schedule-based protocols, in the contention-based approach there is no need for creating clusters as they can support peer-to-peer communications [Ver08] and there is no need for topology knowledge, thereby making contention-based protocols more scalable.

ALOHA and CSMA (Carrier Sense Multiple Access) are typical examples of the contention-based approach. In ALOHA, a node sends its packets whenever it wants; therefore, there is a high probability of collision. In CSMA with Collision Avoidance, nodes sense the channel before trying to send a packet. If the node finds the channel free, then the node starts transmitting its packet, otherwise it backs off and tries again later. Although the back-off mechanism reduces collision probability, the collision avoidance mechanism becomes less effective in dense networks. In dense networks packets may still collide due to an increased number of hidden terminals [Wan02]. In hidden terminal (**Figure 2-4**) situations, two nodes located outside their radio range (A and C) cannot hear each other. They may attempt to transmit to a node B at the same time. In this case, two packets may collide and this results in energy waste in senders A, C and receiver B. In general, CSMA/CA suffers from poor energy efficiency as the nodes listen to the channel to contend and before transmission (idle listening). In addition, as the density of sensor nodes increases, collision avoidance mechanism becomes less effective because of an increase in the number of hidden terminals in the network [Wan02].

To tackle hidden terminal problem in IEEE 802.11 [IEEE99], the transmitting node prior to sending actual data sends a short control packet called Request-To-Send (RTS). The receiver responds with another short Clear-To-Send (CTS) message.

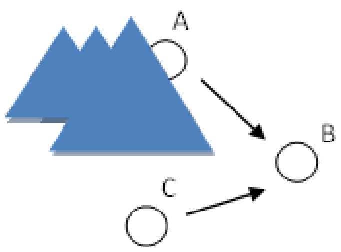

Figure 2-4 Hidden terminal

RTS/CTS handshakes prevent simultaneous transmission of nodes within the transmission range of the receiver node. Although, the RTS/CTS mechanism has been used effectively for IEEE 802.11 systems, in most WSN protocols, such as IEEE 802.15.4 [IEEE03], it is not applied. The first reason is the control-packet handshake mechanism increases overhead. In typical WSN applications, the data length is less than 100 bytes [Wat08] which is far less than IEEE 802.11 (2304 bytes) [Akh06]. Handshaking also increases data delivery latency especially in multi-hop communications. The second reason is RTS/CTS exchange requires all sensor nodes to have their radios on at the same time and this is not energy efficient. Therefore, the RTS/CTS mechanism is only feasible in contention-based MAC protocols with common active periods [Wat08]. The majority of contention-based protocols designed for WSN, especially those which are based on the CSMA/CA technique used in IEEE 802.11, suffer from idle listening (except for a few protocols such as S-MAC [YeH02, YeH04] that have a periodic wake-up scheme as described below).

In **contention-based MAC protocols with common active periods**, sensor nodes adopt a common active/sleep periods. The active periods have been used for contentions and communications and sleep periods for saving energy. Sensor nodes synchronise their sleeps and wake ups by means of synchronisation messages. It is clear that in this approach synchronisation overheads have a negative effect on energy efficiency

Contention-based MAC protocol with a common active period is more suitable for applications that generate regular and periodic traffic (i.e. periodic monitoring, etc.) and applications in which keep-alive beacons are periodically exchanged to ensure network health and reliability. However, in applications with bursty on-off high traffic the use of common active periods may not be suitable as sensor nodes contend in the active period even when they do not have a packet to send, which may cause collisions [Bac10]. In applications that generate high burst of data traffic, the active period should also be large enough to accommodate contention between nodes. In the following, we describe a major MAC protocol that operates in CSMA/CA and discuss the relevant enhancements.

S-MAC (Sensor MAC) [YeH02, YeH04] is a representative example of contention-based MAC protocol with common active period. In S-MAC, nodes periodically turn their radio off (to save energy) and on (to communicate with each other). Active periods are fixed sized while sleep period can be variable. As illustrated in **Figure 2-5**, active period is divided into two sub-periods: one for exchanging *SYNC* and next one for exchanging data and control packets. Therefore, a certain level of synchronisation is required between nodes.

In the initialisation at the deployment phase or when for a sensor node intend to join to the network, node senses the channel for a period of a one active period plus sleep period to check possible SYNC message. In case of receiving SYNC packet, the node synchronises its scheduler and adopt the duty-cycle of the network. If the node does not detect any SYNC, it starts to propagate its own SYNC and follows its own scheduler. Other nearby nodes can join to this network. Once schedulers synchronised, nodes use CSMA in the second sub-period to exchange their control/data packets, similar to IEEE 802.11.

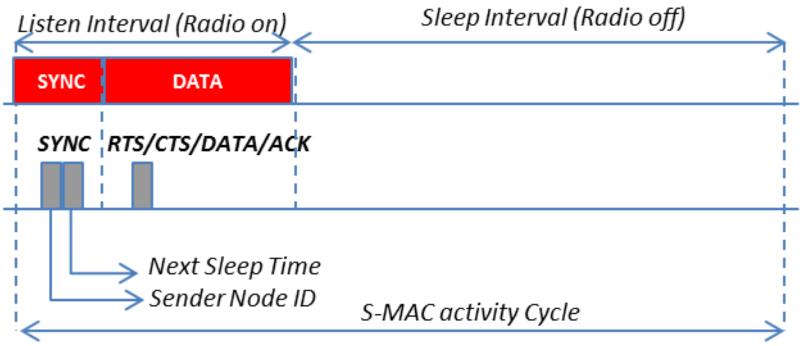

Figure 2-5 S-MAC Operation

Common active periods have various drawbacks such as [Wat08]: using short active periods results in reduction in idle listening whereas it increases contention and collision rates. Having long active periods; however, reduces contention and increase idle listening. In S-MAC, active periods are fixed size that makes the protocol rigid and results in fixed end-to-end delay. Therefore, determining an appropriate trade-off between delay due to sleep period and optimal size of the active period in S-MAC is a challenge.

2.3.3. Preamble Sampling MAC protocols

Most applications of WSNs generate low traffic load and the communication channel is idle in most of the time; therefore, as previously explained, idle listening is the main energy dissipation in such applications [Bac06, YeH04]. By keeping sensor nodes in sleep mode, the main energy saving can be achieved. The ratio of the activity period to the sleep period is generally defined as duty-cycling. By reducing the duty-cycle to 1% or less, a massive savings in energy can be achieved [Bac07]. However, by reducing the duty-cycle, the chance of communication decreases. It is highly possible that a node transmits a packet to its neighbours while they are in sleep mode. Therefore, a mechanism needs to be in place to avoid this situation. Preamble Sampling approach [ElH02], – generally known as low asynchronous power listening (LPL) [Pol04] has been designed to tackle idle listening and support sleep/wake up mode without synchronisation overheads. Each node selects its own sleep/wake up schedules independently of other nodes and nodes spend most of their time in sleep mode, and wake up every Check Interval (CI) for a short duration (called Clear-Channel-Assessment, or CCA) to check whether there is an on-going transmission on the channel. To avoid deafness, each data packet is preceded by a preamble which is longer than CI, to make sure that all potential receivers detect the preamble and then get the data frame. In literature, this approach has been referred to different names, i.e. Cycle Receiver [Lin04], or Channel Polling [YeS06].

2.3.4. Related Works

Some MAC protocols that utilized Preamble Sampling idea are BMAC (Berkeley MAC) [Pol04], WiSeMAC (Wireless Sensor MAC) [ElH03], 1hopMAC [Wat06], and RB-MAC (Receiver-Based MAC) [Akh11, Akh13]. The STEM (Sparse Topology and Energy Management) [Sch02] protocol uses two channels: a wakeup channel and a data channel and other protocols such as CSMA-MPS (CSMA with Minimum Preamble Sampling) [Mah04], TICER (Transmitted Initiated Cycled Receiver) [Lin04], XMAC [Bue06], and MH-MAC (Multimod-Hybrid MAC) [Per07] use techniques to reduce preamble length by packetisation. In MFP [Bac06], the authors have proposed replacing the continuous preamble by a series of small frames. The idea of Micro-Framed preamble is to identify the problem of *overhearing,* the reception of irrelevant frames. Each micro-frame may contain some information e.g. the receiver's address and its rank in the preamble which serves as a countdown timer for receivers. The WOR (Wake On Radio) [CC2500], and SpeckMAC-D [Won06] replace the preamble by actual data packets.

In 1-hopMAC [Wat06], authors have proposed a Micro-framed based protocol in which receiver nodes reply with a time proportional to some metrics. The first replying node is selected as the next forwarder. 1-hopMAC takes the idea of preamble sampling further by allowing a node to dynamically discover its neighbourhood at each transmitted packet. A transmitting node listens between sending the preamble and the data, leaving time for its neighbours to announce themselves. Implementations of 1-hopMAC have shown that, because it does not take link reliability into account, unreliable links cause transient connectivity, which in turn stresses the routing protocol.

2.3.4.1. Pros and Cons

Preamble Sampling MAC solutions are ideal for low-rate data networks. In high-traffic scenarios, if several nodes try to send preamble at almost the same time, there is a probability of collision in the receiving node which may destroy preamble and the data frame. If collisions happen, the senders should retransmit the long preamble and data, which is costly. Rhee et al [Rhe05] have proposed ZMAC which is a combination of TDMA and CSMA. Although it outperforms BMAC in high-traffic scenarios, still it consumes more energy in low-traffic networks. In basic preamble sampling protocol (**Figure 2-6**), transmitting node sends a preamble of length *CI+CCA* duration. When receiver nodes sample the channel, they stay awake until the data message is received. Staying awake until beginning of the actual data is energy-costly for receivers. Bachir et al. in [Bac06] have proposed a solution for this problem. They have divided the preamble into small consecutive micro-frames called micro-frame preamble (MFP). Each micro-frame contains the receiver's address and other information. MFP will avoid receivers from receiving long preamble which is not destined to them (**Figure 2-7**). Buettner et al, have used similar approach in X-MAC [Bue06] to tackle costly collisions in long preamble. They fragmented the preamble into small preambles and listen between each small preamble.

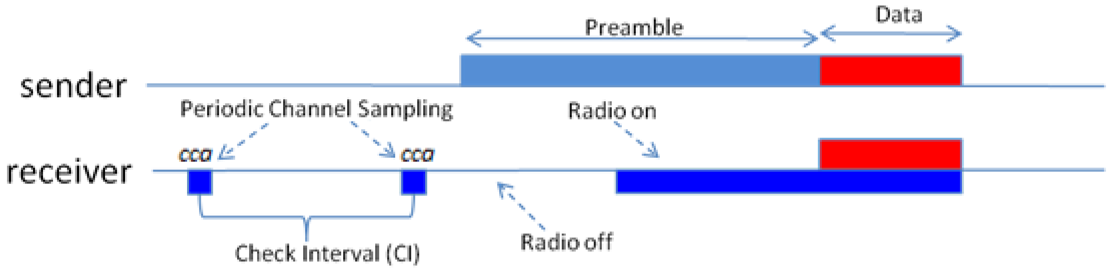

Figure 2-6 Basic Preamble-Sampling

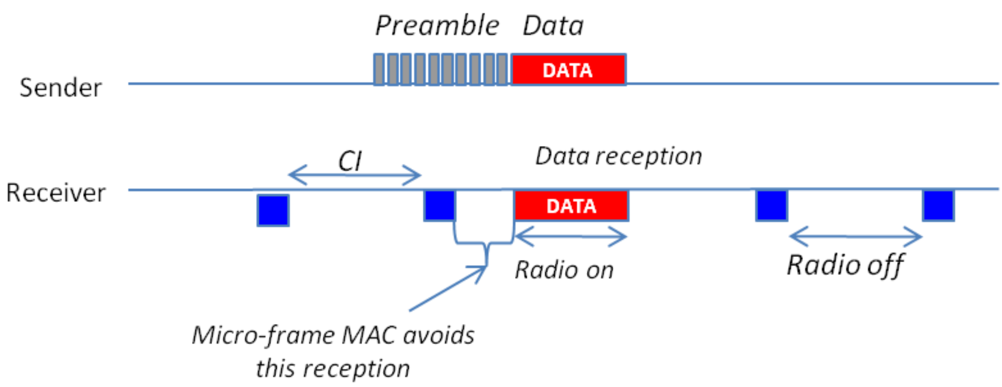

Figure 2-7 Avoiding reception an irrelevant preamble [Bac06]

2.3.5. Hybrid Protocols

Generally a hybrid MAC protocol is a combination of previously discussed MAC classes to take advantages of one's characteristics to compensate the drawbacks of another class under different traffic patterns. For example, when a small number of nodes transmit, contention-based approaches yield sufficient performance; however, when a large number of nodes transmit, then scheduled protocols are a better choice [Bac10]. Several hybrid techniques are exists. As a representative example of this class, we describe IEEE 802.15.4. More hybrid MAC protocols are presented in [Bac10].

2.3.5.1. IEEE 802.15.4

IEEE has standardised 802.15.4 [IEEE03] specifies the physical and MAC layers for low data rate and low power area networks. It is mainly designed to target ZigBee [ZigBee] applications. It supports two types of devices: the full function device (FFD) and the reduced function device (RFD). FFD can form any type of topology and acts as network coordinator; RFD can only act as an end-device and form star topologies by connecting to the FFD's network. From ZigBee applications perspective, only end-devices (RFDs) are resource constrained and need to save energy and FFDs are not battery-powered. IEEE 802.15.4 has two basic operational modes: i) beacon-enabled mode; and ii) non-beacon mode. In beacon-enabled mode, FDD send beacons to maintain a slot structure similar to scheduled-based MAC protocols. In non-beacon is similar to CSMA/CA MAC, has been designed for networks with low complexity nodes. Some weaknesses of IEEE 802.15.4 are [Bac07]: distribution of active/sleep schedules among nodes in an efficient way is a challenge as collisions occurs during beacon transmissions. Moreover, for low traffic load scenarios the overhead of periodically sending and listening to beacons in order to maintain synchronisation may be very costly.

2.4. Summary

For the last decade, a considerable amount of works on channel access protocols has been proposed. In this chapter, we categorised different MAC solutions into four different classes. The main challenge in designing an efficient MAC for WSN is minimising idle listening (to save energy) while maintaining the connectivity between sensor nodes. We briefly studied the protocols and explained few representative examples in each category, followed by pros and cons of each class. We discussed that different applications, traffic patterns, traffic load, and periodicity of reporting require different MAC solutions. For example in monitoring applications, scheduled-based MAC solutions is preferred while for low data rate applications preamble-sampling solution would be a better candidate.

3. RPL: Routing Protocol for Low power and Lossy Networks

3.1. Introduction

Routing protocols are essential components of WSNs, as in other networks. Numerous routing protocols have been proposed for WSNs. In large WSN deployments, some of the sensor nodes are often located a far distance from the sink; and, due to their limited communications range they need to communicate in a multi-hop fashion to reach the sink. Thus, an energy-efficient routing algorithm is essential to prolong the life-time of the network.

As discussed in Chapter 1, the Routing Over Low Power Lossy networks (ROLL) Working Group was formed by the IETF in 2008.[1] The main objective of ROLL Working Group [ROLL14] has been to identify routing solutions for Low-power and Lossy Networks (LLNs). The WG provided a set of requirements and routing metrics (discussed in Sections 1.1 and 4.2) for four main applications of LLNs: urban networks including Smart Grid applications [RFC5548], building automation [RFC5867], industrial automation [RFC5673], and home automation [RFC5826]. In the next step, the WG analysed existing routing protocols against these requirements and realised that none of the existing routing protocols (OSPF, IS-IS, OLSR, TBRPF, RIP, AODV, OLSR, DYMO, DSR) in their current form would fulfil the routing requirements for LLNs. Consequently, ROLL decided to design a new protocol called RPL (Routing Protocol for Low power and Lossy Networks) as a standard routing protocol for LLNs [RFC6550]. In this chapter, we explain the main features of RPL.

3.2. Protocol Overview

RPL is a Distance-Vector (DV) protocol and is designed to operate over different physical and MAC layers including IEEE 802.15.4 PHY. As stated, RPL is specifically designed for lossy links. It should quickly respond to the link failure with no risk of route oscillation. Several techniques have been used to cope with link failure such as Bidirectional Forwarding Detection; BFD (RFC5880), in which traffic is immediately redirected to a backup path to

[1] The author of this thesis is a member of ROLL Working Group since 2008 and this work is considerably influenced by RPL protocol.

minimise traffic disruption [Vas10]. In particular, RPL-enabled LLNs should have two main features: i) prospect data rate is typically low (less than 250 kbps), and ii) communications are prone to high error rate [Gad12]. RPL supports point-to-point, multipoint-to-point, and point-to-multipoint traffic. To support different types of traffics, RPL builds a Directed Acyclic Graph (DAG) in which paths are created in upward direction from nodes towards the root i.e. the sink or Low power and lossy Border Router (LBR). These are called Destination Oriented DAGs, or DODAGs. A DODAG offers redundant paths, which is essential in LLNs, to increase network reliability. If topology permits, there is more than one parent from each leaf node towards the DODAG root [Vas10]. This is in contrast to classical tree-based topologies wherein a node always has to have one parent. This is also an important driver for us to propose RB-MAC to support RPL.

Another feature of RPL is the support of both mesh and hierarchical topologies. Hierarchical topology is based on parent-to-child relationship, whereas in mesh topology traffic can be routed through siblings (nodes with the equal rank) instead of parents and children. This combination mesh/hierarchical provides a great flexibility in routing and topology management [Gad12].

3.3. Network model

RPL defines three types of nodes:

- Low power and lossy Border Router (LBR): root of a DODAG and serves as the sink in WSN. It is a collecting point and can act as a gateway between LLN and the Internet. Usually the Internet gateway powered by the main and has no energy issue.
- Router: intermediate nodes that can generate traffic and relay other nodes' traffic. Router is unlike LBR and is not able to create a new DAG but can join the existing one.
- Host: leaf node or end-devices that can generate traffic only.

Figure 3-1 illustrates “RPL nodes that form a DODAG rooted at a destination node support multipoint-to-point traffic (left). The solid arrows point to a node's preferred parent; the dotted arrows point to other nodes included in the parent set. Rank values for each node are also presented. The DODAG, also supports point-to-multipoint traffic and point-to-point traffic in either a non-storing mode (centre), in which the root attaches source routing headers to data packets, or storing mode (right), in which each node maintains the routing state for its descendants” [KoD11].

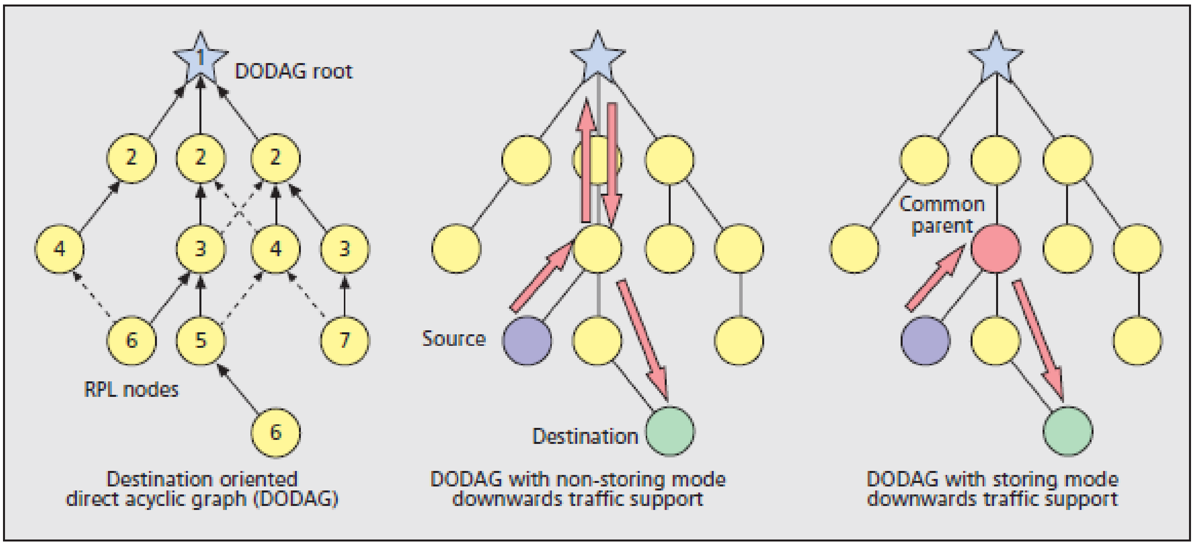

Figure 3-1 RPL nodes that form a DODAG [KoD11]

3.4. The Objective Function

Objective Function (OF) is introduced in RPL to states the outcome of the process used by a node to select and optimize routes and parent node sets within RPL. OF is not an algorithm. For instance, if the link metric is representative of the link propagation delay, the path cost represents the total propagation delay to the destination and the OF may specify finding the shortest path based on the propagation delay [Vas10]. OF expresses how RPL nodes translate one or more metrics into ranks and how to choose and optimise routes in a DODAG [Gad12]. With LLNs, OF may be slightly more complex, for example, OF for alarm reporting (delay sensitive application) is to select a path with minimum delay and high reliability with no constraint on the type of the nodes along the path to destination while for delay tolerant application (telemetry traffic) the OF is to select a path with minimum number of battery-powered nodes to save energy. RPL used two DODAG with each one having its own OF [Vas10]. Another example, be find the path with the minimum delay that does not traverse any non-encrypted link [Vas10].

3.5. Link Reliability

The links utilised in the Internet such as Copper Coax and Optical links are very reliable with very low error rates. That is why Internet routing protocols such as OSPF and IS-IS have not applied reliability as a metric to select a routing path. On the contrary, in WSNs in general and specifically in LLNs, links are highly unstable and variable over time. This implies the addition of link reliability as an important link metric to be used in computing routing path in lossy networks.

Several reliability metrics are defined for lossy links [Bis05] and [Bac06]. The most widely used is the expected transmission count (EXT), which defines the average number of transmissions necessary to deliver a packet successfully [Wat06]. Different techniques for computing ETX have been proposed. In [Bis05], the authors include effects of link loss ratios in two directions (forward and reverse) for each link. A transmitting node sends regular dedicated link probe packets in each direction to compute the delivery ratio for each link. ETX is then defined as $1/\left(d_f \times d_r\right)$ where d_f is the forward delivery ratio (the measured probability that a data packet successfully received by the neighbour).The reverse delivery ratio, d_r is measured probability that the acknowledgement packet is successfully received. Given that probe packets are sent with a regular time interval, both sender and receiver can calculate d_f and d_r.

3.6. Rank

Following the design of RPL, we assume that each node obtains a *rank* in the network which is defined in [RFC6550] as “the node’s individual position relative to other nodes with respect to a DODAG root”. The rank is computed depending on the DODAG’s OF such as hop counts, link metrics, etc. It can indicate the location of a node in a DODAG. The nodes' ranks form a gradient, i.e., the further away from the destination, the larger the rank (DODAG root (LBR) has the rank of 0). Nodes having the same rank are called siblings. In RPL rank value of nodes can change, i.e. a node that moves closer to the LBR can obtain smaller rank than its previous rank.

Figure 3-2 shows the operation of router (intermediate node in DODAG) in a DODAG for constructing routes in downward direction.

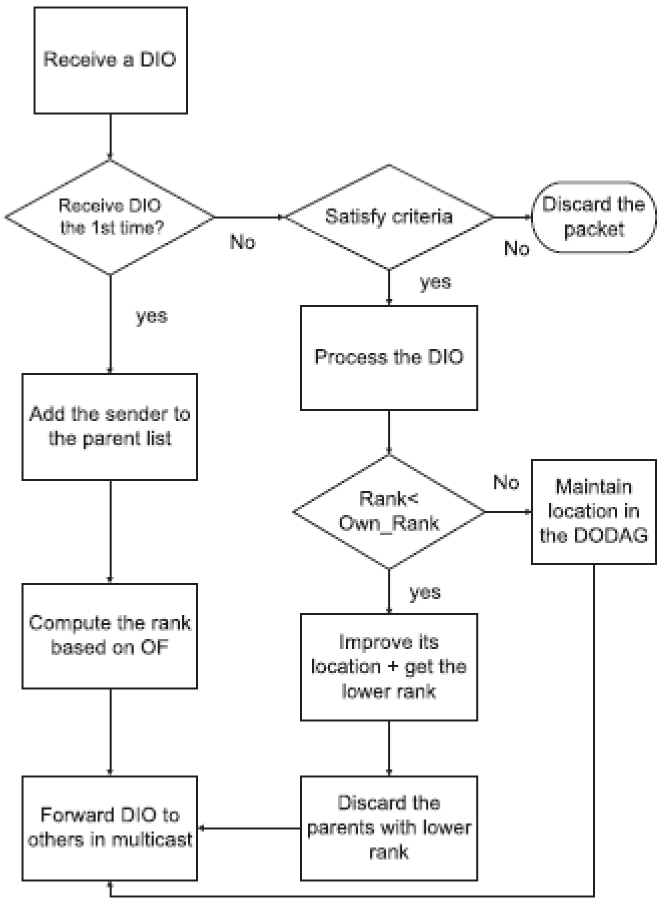

Figure 3-2 The operation of a router in a DODAG

3.7. Control messages

RPL uses following control messages:

- DIO: DODAG Information Object is a multicast control message issued by DODAG root to construct routes in downward direction from LBR to host nodes. Upon receiving a DIO, each intermediate node of the DODAG (router) multicast downwards. If the DODAG structure does not change, the periodicity of issuing DIO increases exponentially.
- DIS: DODAG Information Solicitation is a multicast control message is used when a new node joins the DODAG to solicit a DIO from a RPL node.
- DAO: Destination Advertisement Object is a unicast control message generated from host nodes in upward direction to the LBR along the DODAG to build routes. DAO is used to propagate destination information upwards along the DODAG. The message is unicast by the child to the selected parent to advertise their addresses and prefixes. Upon receiving DAO the message a node updates its routing table.

3.8. Summary

In this chapter, the IETF’s RPL protocol is briefly described. RPL has been designed as a standard protocol for low power and lossy networks. Protocol overview, design objectives, network model and other main features and specifications have been discussed. RPL unlike most of other routing protocols that every node can only have one parent; it can have more than one parent and more than one path to the sink. The secondary parent/path can be used as a backup path when the primary parent is not available. This increases the reliability of the network. A more complete description of the RPL routing protocol is available in [RFC6550] and [Vas10].

4. Target Applications, Requirements, and Assumptions

4.1. Target Applications

Solutions for WSN challenges are highly application-dependent and scenario-based. WSNs can support various deployments in diverse scenarios, such as Machine-to-Machine (M2M) networks [Exa12]. Different applications may require different quality of service (QoS) for data transmission necessitating specific energy, delay and reliability support at node and network. MAC protocols need to be adaptive to cope with these requirements.

In this research, we consider a WSN consisting of a large number of low-power, low-cost sensor nodes with limited transmission range. These nodes are distributed over a vast area and report sensed data towards one or more sinks in a multi-hop fashion. The wireless channel condition and sensor nodes in our case are considered to be lossy with high error rate.

We consider an alarm-reporting scenario in which these alarms are generated by sensors that detect gas pollution (SO2, NOX, CO, Ozone, heavy metals e.g. Mercury, pH, radioactivity, allergens e.g. pollen, dust), electromagnetic pollution and noise level [RFC5548]. Sensor nodes are expected to measure the events and report an alert when levels are increased above a pre-defined a ‘danger level’. In agriculture, a combination of wireless sensor and actuators can be used to protect crops from trespassing animals. Another example would be wildlife tracking wherein wireless sensors could be deployed along a road or railway to report nearby animals before crossings thus preventing fatal traffic accidents. Deployment of the above stated network is likely to be in an outdoor area. Therefore, heterogeneous WSNs can be used in which different powering sources for sensor nodes exist [Akh09]. Solar-powered nodes can be used to extend the life time of the network and by transmitting data on sunny days and battery-powered nodes can be used to increase network reliability on dark cloudy days. Some sensors nodes may use solar power (with regular rechargeable batteries) and some may only have non-rechargeable batteries.

In the above-stated scenario, an alarm or event may not happen frequently, however, once it happens the communication protocols in WSN must ensure the delivery of messages to the intended receivers. In this scenario, the sensor nodes generate low traffic and data-packet size is comparable to control packets. In this scenario, energy efficiency, delay and reliability of data delivery are important factors. This section introduces the main requirements of the described scenario in order to design an appropriate MAC and routing protocols.

4.2. Requirements

The following list is the requirements for communications protocols designed for Low-power and lossy WSNs:

4.2.1. Location

Sensor nodes need to know their physical location and include their location information of the event region in the reported data to the sink. This is because reporting an event without locational information can be useless. Nodes may use GPS or other positioning services to define location information and their final destination. Alternatively, routing information can indicate the distance (i.e. in number of hops) from sensor nodes to the sink. To this end, the proposed routing protocol must provide locational information to the sensor nodes.

4.2.2. Delay

We define delay as required time for transmission of one data packet from a sender node to receiver in a single hop. In other words, the time required for a node to successfully access the channel, time duration of the data packet (including preamble and actual data), and contention window required for a one data packet transmission. We consider delay per hop rather than end-to-end delay. For the sake of simplicity for end-to-end delay we multiply the delay occurred per-hop in the number of hops (assuming that all nodes introduce the same transmission delay the hops have almost the same delay). In this work, we do not consider queuing delay in the buffer, etc. In particular the total time durations of packet sizes

Delay is important for alert reporting. MAC protocol needs to provide low delay in one-hop delivery because routing protocols in WSN are normally in multi-hop fashion and this delay can add one second per hop [YeH04].

4.2.3. Scalability

Scalability implies capability of managing large number of nodes in the network. Solutions for the stated applications need to handle a large number of nodes in network between 250 [RFC5826] to 1000 [RFC5867] and up to 10,000 in [RFC5548]. Taking into account the large scale of WSN, big neighbourhood tables cannot be considered as a right choice for routing decision making and preferably the proposed algorithms should be able to work in a distributed manner rather than through central administration.

4.2.4. Energy-efficiency

In the described scenarios, sensor nodes may sense the environment periodically; however, the desired alert is not expected to happen frequently. Therefore, from a communication point of view, sensor nodes should spend most of their time in sleep mode to maximise the life time of the network. Recent studies show sensors' energy consumption radio communications is much higher than in computation or sensing. Almost all of WSNs in the targeted applications are expected to operate for a long term. Therefore, sensor nodes should work in low duty-cycle. Jian et. al. [Jia05] designed a solar-powered sensor node and predicted their WSN can work for more 40 years if the network operate under 1% load. Although such a life time sounds promising, it seems that the research did not consider the chemical characteristic of the batteries, i.e. leakage.

4.2.5. Reliability

WSNs usually operate in 2.4GHz ISM (Industrial, Scientific and Medical) band and interference from other resources can lead to high PER (Packet Error Rate) in the deployments. In addition, path loss, shadowing and fading can affect the wireless channel and cause considerable fluctuation in channel quality over time [Stu03, Yar02].

Wireless links in WSNs are even more prone to failure due to network dynamicity and topology changes that may occur frequently. Network nodes may be stolen or destroyed without any notification. Nodes may also run out of battery power or be removed from the network due to hardware failure. In some applications new nodes may be injected into the network for better connectivity [RFC5548]. Sensor nodes may move to new positions out of range of their previous neighbours and new communication links can be created with new neighbours. In heterogeneous WSNs consisting of solar-powered and battery powered sensor nodes, the probability of changing network topology is even higher because solar powered sensor nodes may run out of power in the case of continuous cloudy days or if the solar panels are covered by dust and dirt. To this end, the proposed communication technique must be reliable and robust against interference, network dynamicity and high PER.

4.2.6. Traffic Flows

Three main traffic flows for most WSNs can be considered as follows:

- Query requests from the sink (s) towards the sensor nodes (Point-to-Multipoint)
- Reply (sensed information) from the sensor nodes towards sink (Multipoint-to-Point)
- Control commands from the sink (s) towards the actuators, or response (acknowledgment) from actuator to sink (Point-to-Point)

To this end, the communication protocols (MAC and routing) for these types of scenarios should support different traffic flows in particular point-to-multipoint in addition to point-to-point.

4.2.7. Adaptive routing

Due to high dynamicity of these types of networks, routing protocol must be able to compute routes optimised for different metrics (e.g., minimise latency, maximise reliability, etc.) [Vas10]. According to [RFC5867] routing protocol must be able to discover a route that fulfils specific constraints such as a route that provide a packet delivery within some deadline.

4.3. Assumptions

- Location: Each node is aware of its locational information either its geographic location (using GPS, anchor node, etc.) or hop-distance from the sink. We assume that in the initialisation stage of the WSN in which the sink broadcasts a message to all sensor nodes, each sensor obtains its hop-distance from the sink. In RPL routing protocol, the hop-count distance to the sink is called "rank" and RPL provides this.
- Connectivity: The network is considered as connected and each sensor node has at least one neighbour in its communications range to communicate with. The connectivity of a network can be expressed as follows [Aky02]:

$$\mu(R) = \frac{N.\pi.R^2}{A} \tag{4.1}$$

where R is the radius of transmission signal, A the area and N the number of nodes in area A. In [Kle78], it has been shown that when connectivity $\mu(R)$ reaches 6 nodes, the network can be considered as a connected graph because the probability that a node is connected tends to be 1.

- Hidden Node: Based on [Bac07], to guarantee the non-existence of hidden nodes:

$$n_h(r) = 0 \quad if \quad E \geq I(r) + r \tag{4.2}$$

where $n_h(r)$ is the number of hidden nodes, E is signal detection range, (r) is the distance between two nodes and $I(r)$ is the signal interference range. Signal interference range can be obtained by

$$I(r) = r\sqrt[\beta]{TR_{CP}} \tag{4.3}$$

where β is path loss exponent and TR_{CP} is threshold of capture ratio (signal detection range). In ZigBee TR_{CP} $TR_{CP} = 10\ dB$

- To ensure the lossyness of the network, average distance between two neighbour nodes should be considered to be in the transitional region (**Figure 1-2**)
- Outage probability or probability of failure has been defined in different ways e.g. in [Kha05]

$$P_{outage} = P_f \approx \frac{d^k}{snr} \tag{4.4}$$

where *k* is the propagation power loss exponent, usually assumed to be between 2 to 4 and snr is signal to noise ratio. In this work, we define P_f to be the probability that a single transmission fails. The reliability is defined as the probability of successfully delivering the data to the receiver(s).

- Sensor nodes are generating small packets and channel utilisation is low.
- Metrics of interest are energy, reliability, and latency. Throughput is not the major concern

4.4. Summary

In this chapter, we defined the targeted application for our proposed MAC protocols and requirements for the proposed protocol in terms of location, delay, scalability, energy efficiency, reliability, traffic flows, and adaptive routing. We also presented our assumptions in order to guarantee that sensor nodes are aware of their location, they are connected at least to one of their neighbours, and hidden terminal does not affect the connection mechanism.

5. Enhancing Energy Efficiency and Reliability Using RB-MAC

In this chapter, we introduce our proposed Receiver-Based preamble-sampling MAC protocol. Based on the forwarding mechanisms in sensor nodes, we categorize PS-MAC protocols into two groups: Sender-Based MAC and Receiver-Based MAC. First, we explain the operation of a typical sender-based protocol; we then introduce the proposed MAC followed by its performance evaluation. Finally, we conclude the chapter with some remarks on performance of RB-MAC.

5.1. Sender Based MAC (SB-MAC)

As discussed, the connectivity graph formed by networked wireless nodes is highly dynamic. Path loss, shadowing and multipath fading cause the reception power of a signal to vary significantly over time and space. This causes links to break and; hence, the connectivity graph to change (which also happens when nodes (dis)appear or move). Any change in the connectivity graph or channel condition may result in packet loss or packet corruption in receiver nodes. In most MAC protocols, reliability of data delivery can be achieved by retransmitting corrupted/lost packets using some control handshakes, i.e. acknowledgment (ACK). In **Figure 5-1** the source node, S, has four neighbours (A, B, C, and D) within its communication range. According to our assumptions in section 4.3, each sensor node has at least one neighbour in its communications range to communicate with (connectivity) and Each node is aware of its locational information either its geographic location or hop-distance from the sink (location). S intends to send its packets to the sink. As described in Section 4.3, each of the nodes has a rank associated with their distance to the sink (in terms of hop-count or distance to the sink). In a typical sender-based MAC protocol, each sensor has a neighbour table that includes the address of the neighbours, their rank and/or parameters (metrics). Therefore, S can *select* which of its neighbours in the list is the best to forward the packet (e.g. distance to the sink, energy level of the receivers, link quality or any combination of predefined cost metrics). Upon the selection, sender S assigns the address of the particular neighbour to the packet and transmits to the receiver. If the receiver node obtains the packet without error, it replies with an ACK. If the sender S does not receive an ACK massage, it will retransmit the packet until receiving the ACK. In IEEE 802.15.4 a packet can be retransmitted up to seven times [IEEE03] or in 1-hopMAC up to three time. If the maximum number of retransmissions is reached, the network layer chooses another neighbour node as an alternative receiver node. It is clear that retransmissions are costly in terms of energy and delay especially in low-power and lossy WSNs. Moreover, creating and maintaining of the neighbour address table in lossy networks is not energy efficient. **Figure 5-2** presents the timeline of 1-hopMAC as a representative example of a sender-based MAC.

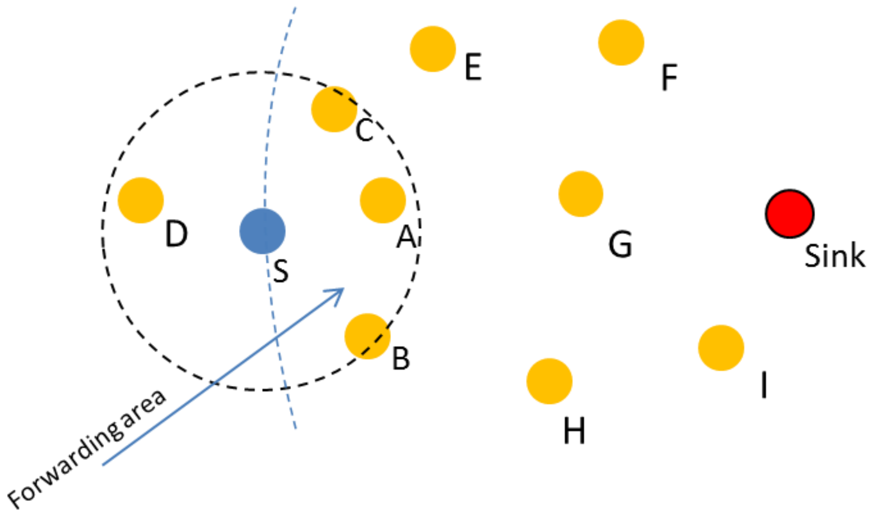

Figure 5-1 Sample Topology, Rank (D) > Rank (S) > Rank (A, B, C) > Rank (Sink)

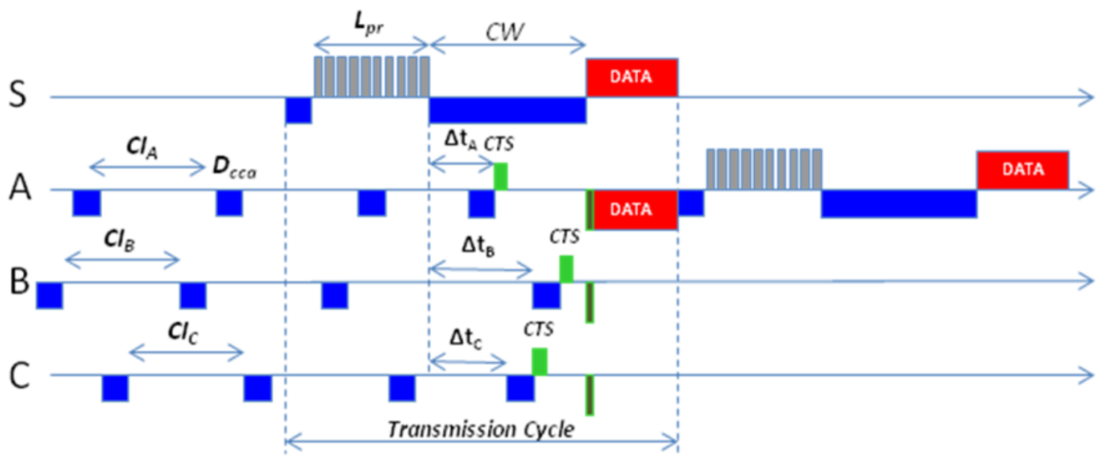

Figure 5-2 Timeline of 1-hopMAC, A box above/beneath the line indicates the radio is transmitting /receiving, respectively.

5.2. Proposed Receiver Based MAC (RB-MAC)

Wireless communications are broadcast in nature and transmitted data over wireless links can be received by multiple receivers. RB-MAC is a reactive MAC protocol that makes particular use of multiple reception of the packets by neighbours to reduce the number of retransmissions in lossy channel.

A group of nodes running the RB-MAC protocol cooperatively *elect* the neighbour, which has a strong link to the sending node and can offer routing progress. In the case of using RB-MAC in **Figure 5-1**, sender S, includes its rank in the micro-frames of the preamble and transmits without defining a particular node as receiver. All the nodes within communications range of S detect the on-going transmission and receive a small part of the preamble. Based on the information extracted from preamble, all nodes compare their own rank with the sender's rank. A node (e.g. D in **Figure 5-1**) discards the packet if its rank is higher than sender's and goes back to sleep mode. Other nodes closer to the sink (A, B, C in **Figure 5-1**) obtain the packet. At this stage if any of receiver nodes (A, B, and C) receives the packet with error, it is simply discarded. Nodes that have received the packet without error start to compete with each other to forward the packet to the next hop. A node which is more eligible than others (e.g. is closer to the sink or has higher remaining energy, etc.) will trigger and forward the packet earlier than other nodes and wins the competition. When other competing nodes attempt to forward the packet with delay, they sense the channel and if they realise that another node is already forwarding the same packet, they drop the packet and go back to the sleep mode.

Flow chart of operation of Receiver-Based MAC protocol in receiver and sender nodes is shown in **Figure 5-3** and **Figure 5-4** respectively. RB-MAC approach can be applied to different classes of MAC protocols explained in Section 2.3; however, by considering the targeted application and scenarios described in Chapter 1 and 4, we realised that the ultra-low power preamble sampling MAC (PS-MAC) [Bac06, Wat06] is the most suitable MAC category as a base for RB-MAC. This is mainly due to the fact that alarms/events may rarely happen and sensor nodes can spend most of their times in sleep mode and operate in very low-duty cycle (in the order of 1%). Moreover, PS-MAC releases the need for scheduling or synchronisation between nodes, and each node can set its own active/sleep schedules. This is important because each node, depending on the availability of the energy can set its own duty cycle (e.g. solar-powered nodes on sunny/cloudy days can increase/decrease their duty cycle).

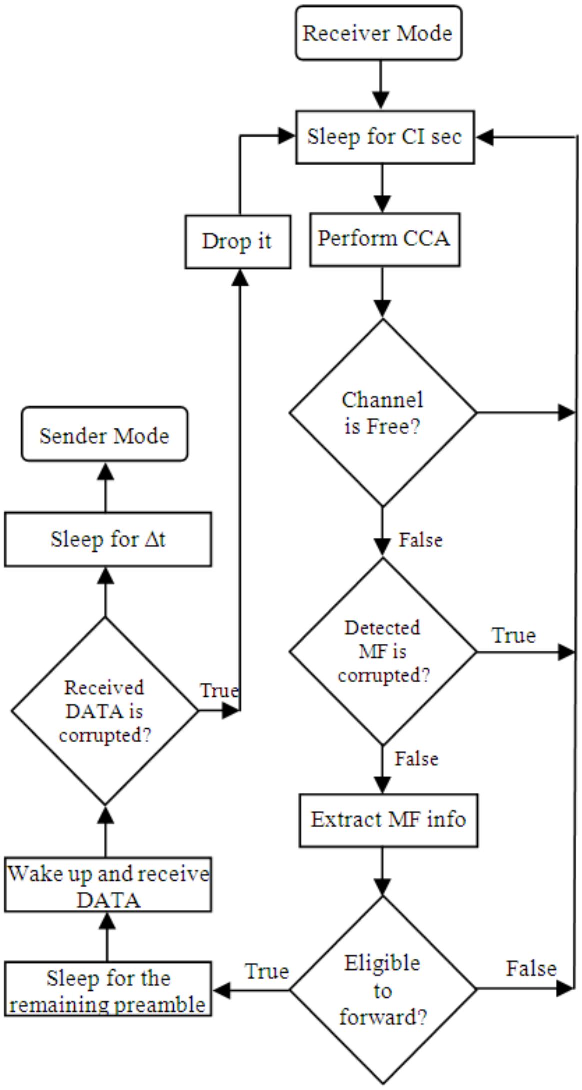

Figure 5-3 Flow chart of receiver node operation under Receiver-Based MAC protocol (MF=Microframe, CI=Checking Interval, Clear Channel Assessment)

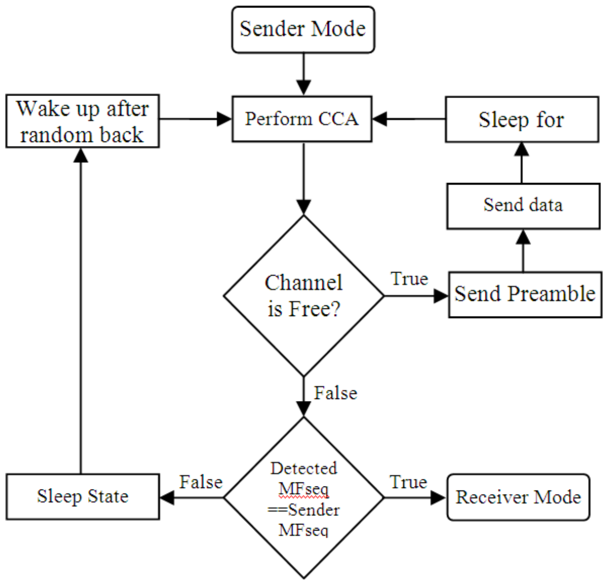

Figure 5-4 Flow chart of sender node operation under Receiver-Based MAC protocol

The chronogram presented in **Figure 5-5** presents the operation of preamble sampling RB-MAC for the sample topology in **Figure 5-1**. As described in Chapter 0, in preamble sampling MAC, each node listen for a very short time (D_{cca}) to every Check Interval (*CI*) to recognise whether it is an on-going a transmission or not. Nodes are not synchronised and may listen to the channel at different times. A sender node pre-pends the data with a preamble. By having the preamble at least as long as *CI*, the sender insures all its neighbours are awake when sending the data. *CI* values of 100ms is commonplace, although the optimal value depends on the amount of traffic carried by the network. MFP [Bac06] and X-MAC [Bue06] extend this idea by cutting the preamble into micro-frames; each micro-frame contains a decreasing counter which indicates when the data will be sent. Upon hearing a micro-frame, a neighbour node can sleep for the remainder of the preamble.

In **Figure 5-5**, when a sender node, S, has a packet to send, it transmits a preamble followed by actual data, without assigning a particular neighbour as receiver. The preamble consists of a succession of micro-frames serving as countdown. Each micro-frame contains the sender's rank, sink's rank, information about the packet such as packet's identification, priority, delay-sensitive/delay tolerant packet and other routing metric.

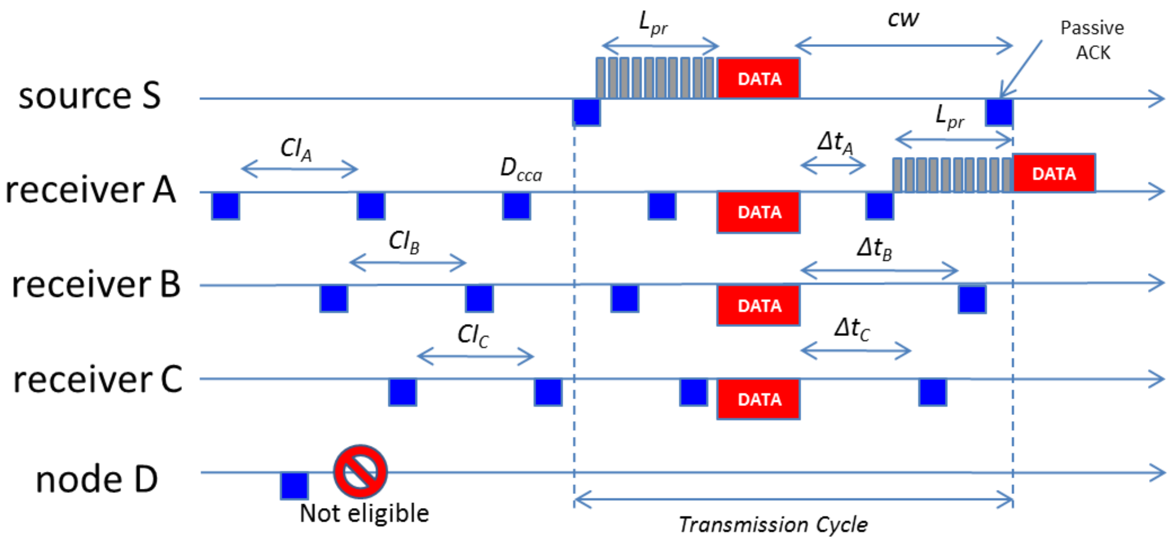

Figure 5-5 Timeline of RB-MAC
A box above/beneath the line indicates the transmitting/receiving.

Nodes A, B, C and D obtain few micro-frames during their D_{cca} period. Node D refrains from participating in the election process because it has a greater rank than S, i.e. it would provide negative progress. Upon receiving the data, nodes A, B and C start a back-off timer proportional to their rank. Because it is closest to the destination, A's timer elapses first. A starts relaying the data; and; upon hearing this activity, B and C cancel their timers. This can be done by extracting the on-going packet's reference from the detected micro-frame. As we already explained in section 4.3, we assumes the non-existence of hidden nodes (this is possible by assuming larger channel sensing than communication range.) If none of the participating nodes in the Contention Window (*CW*) period are successful to forward the data packet, the sender node (S) can realise this by performing CCA just before ending *CW* (passive ACK). Only in this case the sender node will retransmit the data.

RB-MAC allows a sender node to dynamically forward the packet to the next hop and there is no need for maintaining a neighbour table. In [Mac09], authors reported the great data delivery ratio and reduced energy consumption that can be achieved by removing the neighbour table. Moreover, RB-MAC inherently uses current channel conditions. It is different from 1-hopMAC in that the neighbours cooperatively perform the selection, not the sender. As shown later in this thesis, this increases reliability while reducing energy consumption and latency. Implementations of 1-hopMAC show that, because it does not take link reliability into account, unreliable links cause transient connectivity, which in turn stresses the routing protocol.

The cost of this improvement is receptions of data packets by all neighbour nodes having a rank lower than the sender's rank. Since WSN data packets are typically small the energy consumed by the neighbours is negligible in comparison to receiving long preambles in case of retransmissions.

5.3. Related works

Receiver-based forwarding technique has been introduced in several works such as MIT's Opportunistic Routing, ExOR [Bis05], Virginia's IGF [Blu03], GeRaF [Zor03], [Fus03], [LiS08], and [XuL05]. They come under opportunistic routing and gradient routing protocols and receivers decide whether or not to forward the packet. In [Mac09], an energy-aware MAC protocol proposed for receiver-based routing protocols such as GeRaF and IGF. The proposed scheme does not need to keep and update a neighbour table, thus saving energy.

In RB-MAC we adopt a similar concept. It is similar to ExOR [Bis05] as both function in an opportunistic manner. ExOR integrates routing and MAC protocols to improve the throughput of IEEE802.11 wireless networks. In ExOR, the transmitting node forwards the packet to the subset of its neighbouring nodes which could bring the packet closer to the destination. Unlike ExOR, in RB-MAC, the source node does not include in each packet a list of candidate forwarders before sending them to neighbours. While cooperative diversity has been used in ExOR for increasing the throughput of wireless networks, we will show in the next chapter that more energy saving in our proposed MAC protocol can be achieved by using cooperation.

In this thesis, we apply receiver-based forwarding concept to a state-of-the-art preamble-sampling MAC protocol. RB-MAC does not use acknowledgment packets and is a purely reactive. It only uses passive ACK by listening to the on-going preamble. By using adaptive preamble and adaptive checking-interval, we limit the number of receiver nodes. This makes the sender node to send the packet to a subset of receiver nodes and receiver nodes can independently decide whether to participate in the forwarding process. Moreover, while receiver-based forwarding has been used in geographic and tree-based routing protocols, we apply RB-MAC to the state-of-the-art RPL protocol, which is a distance-vector routing over graph-like topology especially designed for low-power and lossy networks.

5.4. Performance Evaluation

In this section, we evaluate the performance of RB-MAC by rather simple analysis for proof of concept. We compare the results with that of a sender-based MAC such as 1-hopMAC. In Chapter 6, we will evaluate this in more analytical detail.

We assume sensor nodes are deployed according to a Poisson distribution of density φ. That is, the probability of finding *i* nodes in an area of size *A* is:

$$P(i,A) = \frac{(\varphi A)^i}{i!} e^{-\varphi A} \tag{5.1}$$

Follows the node degree:

$$N = \varphi \pi R^2 \tag{5.2}$$

5.4.1. Higher Reliability

We call p the probability that a receiver successfully receives the data from S without error. We call outage p_f the probability that a single transmission fails, which triggers retransmission. When using 1-hopMAC, the outage probability is $(1-p)$, because 1-hopMAC only relies on one of its neighbours and tries to retransmit the faulty transmission. In contrast, RB-MAC forwards the data to all eligible neighbours, causing the outage probability to decrease. To calculate outage probability in RB-MAC (i.e. $P_X(x)$), we consider a Bernoulli distribution, which takes value 1 with success probability *p* and value *0* with failure probability $p_f = (1-p)$. Assuming *X* is a random variable, we have:

$$P_X(x) = C_n^x p^x p_f^{n-x} \tag{5.3}$$

where *n* is the number of candidates. The number of x-combinations from a given set *S* of *n* elements is denoted by C_n^x. In RB-MAC, outage happens when none of the candidates receives the packet. In other words, for a successful transmission to happen, at least one of the candidates has to successfully receive the data. The outage probability in RB-MAC can be calculated as:

$$P_X(x=0) = p_f^n \tag{5.4}$$

The outage probability drops to $(\mathbf{1}-\boldsymbol{p})^{\boldsymbol{n}}$. For example, if *n*=4 and *p*=0.80, when replacing 1-hopMAC by RB-MAC, the outage probability drops two order of magnitude from 20% to 0.16%.

Probability of a successful transmission for *n* nodes in RB-MAC is:

$$P_X(x \geq 1) = 1-(1-p)^n \tag{5.5}$$

Probability of retransmission (P_{Ret}) for 1-hopMAC is *(1-p)* and for RB-MAC is:

$$P_{Ret} = (1-p)^n \tag{5.6}$$

Table 5-1 shows the different probabilities of success, failure and retransmissions for 1-hopMAC and RB-MAC.

Table 5-1 Probabilities and Retransmissions

Protocol	Probability of success	Probability of failure	Outage probability	Probability of retransmission	Number of retransmissions
1-hopMAC	p	p_f	$(1-p)$	$(1-p)$	$\frac{1}{p}$
RB-MAC	p	p_f^n	$(1-p)^n$	$(1-p)^n$	$\frac{1}{(1-(1-p)^n)}$

5.4.2. Lower Energy Consumption

Outage translates into retransmissions, which consumes energy. **Figure 5-6** illustrates the energy consumed by the sender and its neighbours when one packet is transmitted. This figure also includes the energy needed to retransmit. **Figure 5-6** shows how 1-hopMAC consumes more energy as links become lossy. Because of its cooperative nature, RB-MAC triggers fewer retransmissions; its energy consumption is not significantly impacted by lower link probabilities. The total energy consumption for a successful delivery is given by:

$$E_{tot} = E_{basic} \times Number\ of\ Retransmissions \tag{5.7}$$

$$E_{tot} = \frac{E_{basic}}{1-(1-p)^n} \tag{5.8}$$

where E_{basic} is the necessary energy for one transmission.

Based on the timelines of 1-hop-MAC and RB-MAC in **Figure 5-2** and **Figure 5-5**, we can calculate the Energy consumes in transmitter node (E_{Tx}) and receiver node for RB-MAC and 1-hopMAC. In RB-MAC:

$$E_{Tx} = D_{cca}P_{listen} + E_{Request} + D_{DATA}P_{Tx} + (D_{CW} - 2D_{cca})P_{sleep} + D_{cca}P_{Rx} \tag{5.9}$$

$$E_{Rx} = \left(D_{REQ} + D_{CW} - 2D_{cca}\right)P_{sleep} + (D_{DATA} + D_{cca})P_{Rx} + D_{cca}P_{listen} \tag{5.10}$$

As we may have more than one receiver in RB-MAC the total energy consumes in RB-MAC would be:

$$E_{basic} = E_{Tx} + NE_{Rx} \tag{5.11}$$

In 1-hopMAC:

$$E'_{Tx} = D_{cca}P_{listen} + E_{Request} + D_{CW}P_{listen} + D_{DATA}P_{Tx} \tag{5.12}$$

$$E'_{Rx} = \left(D_{REQ} + D_{CW} - 2D_{cca}\right)P_{sleep} + (D_{DATA} + D_{cca})P_{Rx} + D_{cca}P_{listen} \tag{5.13}$$

$$E'_{basic} = E'_{Tx} + E'_{Rx} \tag{5.14}$$

To ensure a fair comparison between 1-hopMAC and RB-MAC, we used the energy measurements in **Table 5-2** and **Table 5-3** have been taken from [WiFly].

Table 5-2 Consumption of individual radio states in EM2420 Module [WiFly]

P_{sleep}	8.02 mW
P_{listen}	65.83 mW
P_{Tx}	66.16 mW
P_{Rx}	70.69 mW
$E_{Request} = E_{Preamble}$	1.24 mJ
E_{Tx}	3.50 mJ
E_{Rx}	1.80 mJ

Table 5-3 Timers and Durations

D_{ACK}	480 µs
D_{DATA}	4 ms
D_{cca}	1444 µs
D_{CW}	30 µs
$D_{REQ} = D_{Preamble}$	144ms

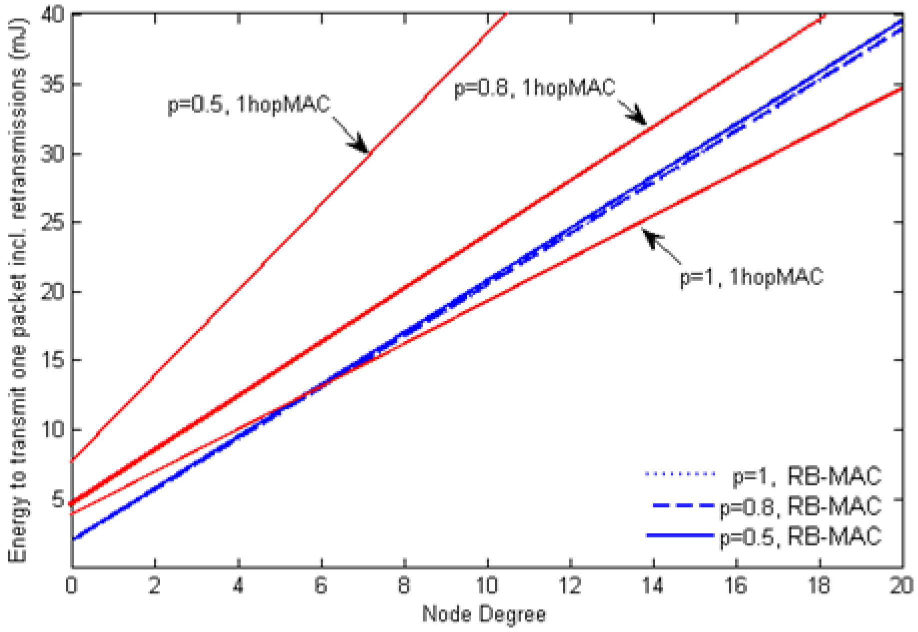

Figure 5-6 Total energy in RB-MAC and 1-hopMAC. RB-MAC is more energy-efficient with lossy links. *p* represents the probability of a successful transmission for one node.

5.4.3. Lower Delay

Similar to energy performance, delay can be obtained as follows:

$$D_{tot} = \frac{D_{basic}}{1-(1-p)^n} \tag{5.15}$$

where D_{basic} is the delay for one packet transmission. **Figure 5-7** presents the performance of RB-MAC versus 1-hopMAC in terms of delay. Delay value for 1-hopMAC remains constant as the node degree increases. This is because 1-hopMAC is a sender-based protocol and only relies on one receiver, therefore; by increase of the number of receivers does not affect the delay caused by retransmission of the receiver. On the other hand in RB-MAC, as the number of receiver nodes increased, the probability of receiving a packet by them increases and the probability of retransmission decreases, therefore; RB-MAC outperforms 1-hopMAC in terms of delay.

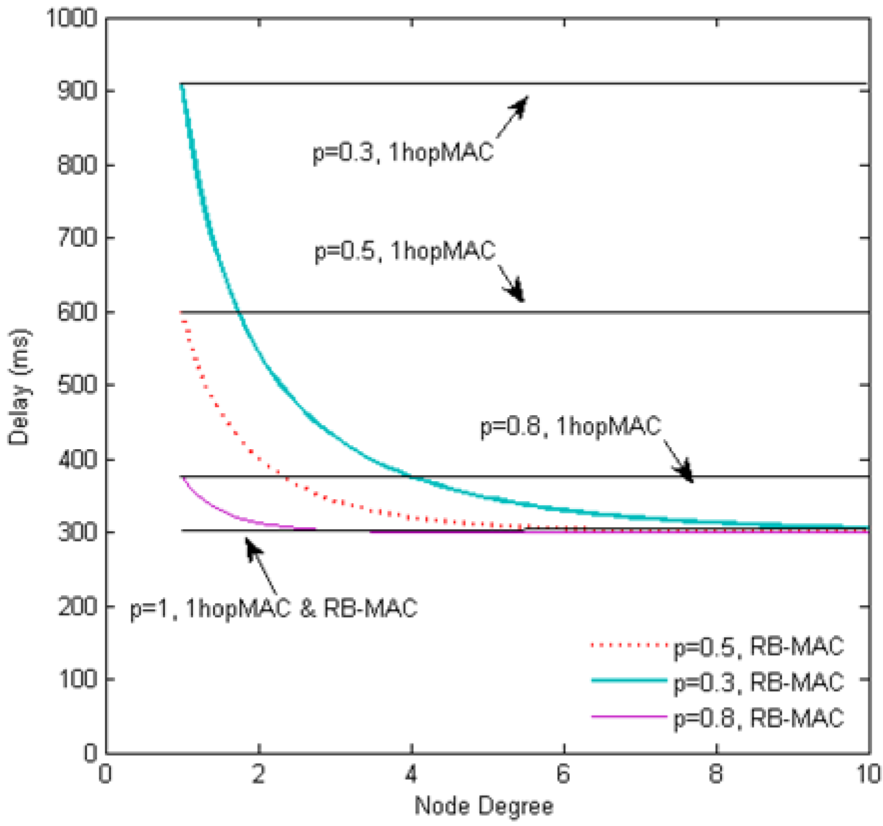

Figure 5-7 Delay performance in RB-MAC. *p* represents the probability of a successful transmission for one node.

5.5. Conclusion

RB-MAC uses cooperation at the MAC layer to elect the next-hop node, rather than selecting one of the neighbours by the sender. It is significantly more resilient to lossy links compared to solutions without cooperation such as 1-hopMAC. This results in fewer retransmissions and increased energy-efficiency than sender-based MAC protocols. In Chapter 8 implementation of RB-MAC with off-the-shelf hardware has been done. Experimental results help assess link-outage probabilities in more realistic usage scenarios.

6. Proposed Adaptive RB-MAC

In this chapter, we propose two extensions for RB-MAC protocol by utilizing the concept of adaptive preamble and adaptive checking intervals. We investigate the performance of the proposed MAC protocols in terms of energy-efficiency, lifetime and reliability. A sender node in our RB-MAC protocols dynamically elects the receiver(s) among a number of potential neighbour nodes. The protocols are resilient to lossy links due to involvement of multiple receivers, yet more energy efficient as they reduce the number of retransmissions. The proposed schemes are an attempt to achieve a good trade-off between reliability and energy-efficiency.

6.1. Receiver-based MAC (RB-MAC)

We start with a brief summary of RB-MAC. As explained in previous chapter, in RB-MAC, a sender node transmits its data without defining the address of a particular node as a receiver. All neighbouring nodes within communication range of the sender node receive the data packet. Based on the information received from the micro-frame (i.e. sequence number of the data, how many micro-frame remains before the actual data arrive, distance of the sender to the sink), each node decides if it is “eligible” (e.g. closer than sender node to the sink) to participate in forwarding the data. Receivers compete in an “election” process to forward the message to the next node and the winner of this competition, forward the data to the next hop towards the sink.

Figure 6-1 shows the timeline of RB-MAC protocol. In this figure sender node S tries to forward its data to the 1st hop neighbours. First, it senses the channel to ensure that there is no on-going transmission (performs CCA). If the channel is free, it starts transmitting the preamble followed by the data. All nodes within the communication range of node S detect and sample few micro-frames of the preamble. They all extract the information in the micro-frame. In this figure, only three neighbouring nodes of node S are eligible to relay data towards the sink node (e.g. they are closer to the sink than node S). They all wake up to receive the data from sender S. If the received data packet is detected to be erroneous, it is simply discarded. The nodes which successfully received the data, do not send any ACK message; however, they set a timer (Δt) before forwarding the data to the next hop. The set time is e.g. relative to the receivers' distance to the sink. The node with the shortest timer is the one that will forward the data towards the sink. Immediately after expiry of the timer, each relay node (such as B and C in **Figure 6-1**) performs CCA.

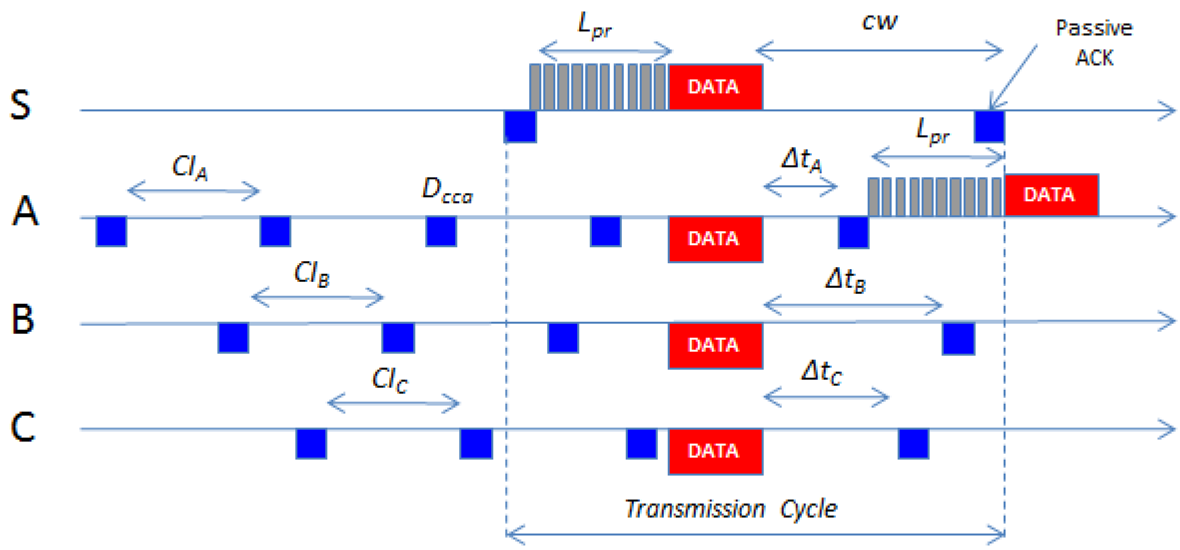

Figure 6-1 Timeline of RB-MAC

If the channel is detected as busy, it checks the sequence number of the detected micro-frame and compares it with its own. If the sequence numbers are equal it means that the same data is being transmitted by another node. Therefore, it discards the data packet. Otherwise, a free channel indicates that this node is the winner and can start sending preamble frames (A in **Figure 6-1**). The above scenario continues and node A tries to send data towards the sink node using the same election process. If none of the participating nodes in the Contention Window (*CW*) period are successful in forwarding the data packet, the sender node (S) can realize this by performing CCA just before ending *CW* (passive ACK). Only in this case the sender node will re-transmit the data. In [Akh11] the authors have reported the performance of RB-MAC in lossy networks. They concluded that RB-MAC outperforms typical sender based MAC protocol in terms of energy and delay due to more retransmissions in sender-based protocol.

6.2. Adaptive PS-MAC

SB-MAC and RB-MAC are two extreme techniques to deal with energy and reliability. SB-MAC only relies on one next-hop receiver node and provides better energy efficiency with less reliability while RB-MAC engages all the next-hop receiver nodes to increase reliability but in good channel conditions it's performance is not better than SB-MAC. The following two proposed adaptive PS-MAC protocols combines the benefits of SB-MAC and RB-MAC to counter the drawbacks of each. ap-MAC and as-MAC proposed in this work overcome the drawbacks of the SB-MAC as they do not maintain the address table. Meanwhile they reduces the probability of retransmissions in lossy networks by employing multiple receivers to increase reliability of data delivery. On the other hand, by dynamically changing the preamble size and check intervals; the permissible number of receivers in RB-MAC are decreased to save further energy. In the next section, we evaluate how adaptive PS-MAC is resilient to lossy links, but is yet more energy efficient than RB-MAC.

In adaptive PS-MAC, we investigate two combinations of adaptability: ap-MAC (adaptive L_{pr}, fixed *CI*), and as-MAC (adaptive *CI,* fixed L_{pr}).

6.2.1. ap-MAC

As stated in the previous sections, in RB-MAC all the eligible nodes within the communication range of the sender node are able to detect the preamble and receive the data packet. This is irrespective of network density or channel quality. In dense deployments, or under good channel conditions, it is most likely that the number of receivers that can receive the data packet without error is high. Receiving the data packet in such a high number of receivers in this case is waste of energy although the size of packet's payload in comparison to preamble size is trivial.

The ap-MAC is a receiver-based MAC protocol with similar mechanisms described in RB-MAC section. In ap-MAC all the nodes have fixed *CI* values and sample the channel in equal time intervals. In contrast to RB-MAC, in ap-MAC a sender node can define shorter preamble size based on one or more metrics (e.g. energy level of the sender node, data delivery delay, etc.). The main objective of shortening the preamble size is to reduce (filter) the number of neighbouring nodes within communication range of the sender node that can detect the preamble. By reducing the preamble size the number of nodes that receive the data packet will be less than that of RB-MAC. Consequently shorter preamble size can lead to energy saving in the sender node and lower data delivery time to the next hop. Moreover, the adaptive preamble scheme can be used in a delay/energy budget scenario, in which end-to-end delay/energy should not exceed a predefined time/Joule. In this approach, each sender node can determine its preamble size based on the remaining time/energy budget (as long as it somehow knows this information). This issue is part of our future research.

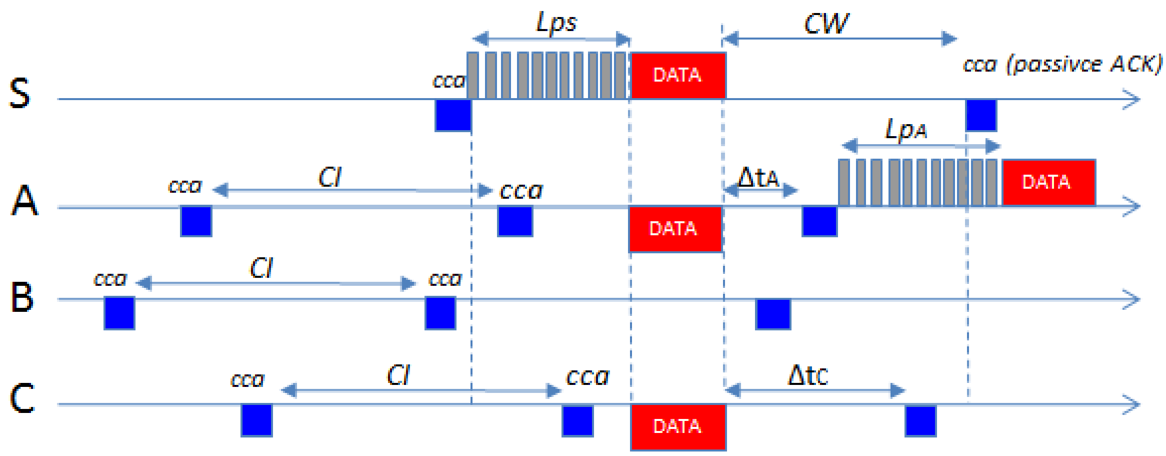

Figure 6-2 Timeline of ap-MAC (adaptive preamble and fixed CIs)

Figure 6-2 illustrates the ap-MAC in which preamble size of node S ($L_{pS} = L'_{pr}$) is less than checking intervals of receiver nodes (*CI*). Therefore, only some of the eligible nodes (A and C) are able to detect the sender's preamble. In this figure, A and C start to compete to forward the DATA and node A becomes successful in the competition and starts sending data to the next hop. It chooses its preferred preamble length that is shown by L_{pA} and data is forwarded towards the sink node following the same approach.

6.2.2. as-MAC

In some sensor network rollouts, sensor nodes have different power sources. Some nodes may use energy harvesting and their batteries are frequently charged; some may only use non-rechargeable batteries. In such networks, different routes for different traffic types may be preferred. For example to report a non-emergency periodic notifications, energy-aware routes should be preferred. While for reporting an alarm more reliable routes need to be used and hence energy efficiency of the route is of secondary importance. The adaptive sampling MAC (as-MAC) is a receiver-based MAC protocol in which receiver sensor nodes can voluntarily participate in forwarding the packets based on their individual metrics. In as-MAC the size of the preamble is considered to be fixed while each receiver sensor node independently adapts its own *CI* based on its residual energy, energy harvesting rate or any combinations of different metrics. In this scheme, nodes with higher (lower) harvesting rate or higher (lower) residual energy are likely to sample the channel more (less) frequently. In this case, the probability of detecting a sender's preamble and participating in the competition for high (low) powered nodes will be high (less). In multi-hop scenario, the last sensor node to the sink will send the data packet instantly without preamble, because the sink is presumed to be active all the time.

Under poor channel conditions, some of the transmitted packets will be corrupted. This requires one or several retransmissions. Therefore, if a sender decides on a short preamble length, it consumes less energy and wastes less time. These benefits come at the cost of lower reliability, since the probability of detection of a micro frame in the preamble stream decreases for the receiver nodes with longer amounts of CI. The above fact has been formulated in section 6.3.3.

Timeline of as-MAC protocol is illustrated in **Figure 6-3** . In this figure, each of the competitors (nodes A, B and C) choose its own amount of CI independently.

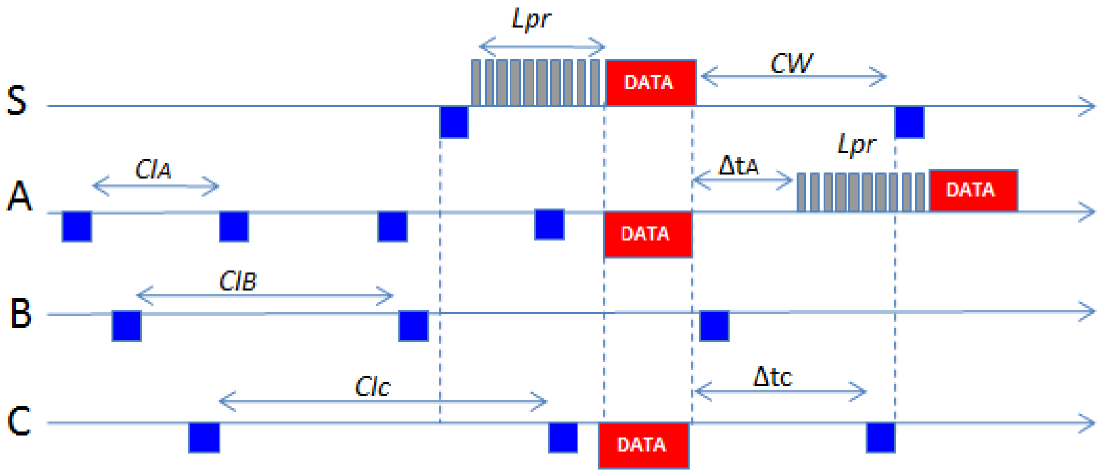

Figure 6-3 Timeline of as-MAC (adaptive CIs and fixed preamble)

6.3. Analytical Modelling

In this section, we evaluate the performance of SB-MAC, RB-MAC, and adaptive PS-MAC protocols (ap-MAC and as-MAC) in terms of total energy consumption, lifetime, and reliability. Our analysis is based on simple noisy Binary Symmetric Channel (BSC) in which a bit has independent probability of failure *p* [Bac09]. The length of one micro frame is considered as a unit size given by T_m. Hence, the whole data packet has time duration of $T_d = r_d T_m$. If P_s represents the power consumption of channel sampling, then energy drained during channel sampling will be $e^s = (\tau + Tcs)P_s$.

Notations and Symbols used in this chapter are described in **Table 6-1**. We use these notations and symbols in the next section to formulate energy consumption, lifetime, and reliability.

Table 6-1 Notations and Symbols

d	data frame size in bits
m	micro-frame size in bits
n	number of retransmissions
CI	checking interval
L_{pr}	preamble length
L'_{pr}	preamble length in ap-MAC
N	number of receivers in RB-MAC
M	number of receivers in ap-MAC
V	number of receivers in as-MAC

p	probability of failure of bit error probability
p_{CTS}	probability of failure of CTS packet
p_m	probability that a micro-frame is corrupted, $p_m = 1-(1-p)^m$
p_d	probability that a data frame is corrupted, $p_d = 1-(1-p)^d$
p_f	probability of failure of a single transmission
T_m	transmission time of one micro-frame
T_d	transmission time of one data packet
τ	transition time from sleep mode to active mode
T_{CS}	the carrier sense duration
T_{CTS}	the clear to send duration
T_{CW}	the contention window duration
P_r	power drained in receive mode
P_t	power drained in transmit mode
P_s	power drained in sampling mode
r_d	data duration in the unit of T_m, $r_d = \left\lceil \frac{T_d}{T_m} \right\rceil$
r_m	number of micro-frames transmitted in preamble, $r_m = \left\lceil \frac{L_{pr}}{T_m} \right\rceil$
r'_m	number of micro-frames transmitted in preamble, $r'_m = \left\lceil \frac{L'_{pr}}{T_m} \right\rceil$
r_{CW}	number of micro-frames transmitted in preamble in ap-MAC contention window in the unit of T_m

6.3.1. SB-MAC

The contention window interval is r_{CW} times the unit size i.e., $T_{CW} = r_{CW}T_m$. The probability of failure for a single transmission would be:

$$p_f = 1-(1-p_m)(1-p_d)(1-p_{CTS}) \tag{6.1}$$

where p_{CTS} is failure probability of CTS packet. The energy drained in a successful and failed transmission are given by

$$e_{succ}^t = e^s + ((1-p_m)(r_mT_m) + (1-p_d)T_d)P_t + T_{CW}P_r \tag{6.2}$$

$$e_{fail}^t = e^s + p_m(r_mT_m)P_t + \left((1-p_m)r_mT_m + p_d\frac{T_d}{2}\right)P_t + T_{CW}P_r \tag{6.3}$$

For one receiver node, we consider average time of wake up to be half of a Micro-Frame (MF). This adds $T_m/2$ time to the Tm time required for a complete reception of a MF. Hence for the receiver node the above two energies are written as:

$$e_{succ}^{r} = ((1-p_m)\left(\tau + \frac{3}{2}T_m\right) + (1-p_d)(\tau + T_d))P_r + (1-p_{CTS})(\tau + T_{CTS})P_t \tag{6.4}$$

$$e_{fail}^{r} = p_m\left(\tau + \frac{3}{2}T_m\right)P_r + 2(1-p_m)\left(\tau + \frac{3}{2}T_m\right)P_r + p_{CTS}(\tau + T_{CTS})P_t + (1-p_{CTS})(\tau + T_{CTS})P_t + p_d(\tau + T_d)P_r \tag{6.5}$$

6.3.2. RB-MAC

N shows the number of receivers in the sender's neighbourhood. Failure Probability of a single transmission depends on the correct or incorrect reception of preamble packets and data. This is shown by:

$$p_f = 1 - (1-p_m)(1-p_d) \tag{6.6}$$

The whole preamble length is called L_{pr} which contains $r_m = \left\lceil \frac{L_{pr}}{T_m} \right\rceil$ micro frame packets. In RB − MAC we know that $T_{CI} = L_{pr}$. Energy drained in transmitter in successful and failed transmissions are as follows:

$$e_{succ}^{t} = e^{s} + \big((1-p_m)(r_m T_m) + (1-p_d)T_d\big)P_t \tag{6.7}$$

$$e_{fail}^{t} = e^{s} + p_m(r_m T_m)P_t + \big((1-p_m)(r_m T_m) + p_d T_d\big)P_t \tag{6.8}$$

The energy drained in a receiver node in a successful single transmission is:

$$e_{succ}^{r} = ((1-p_m)\left(\tau + \frac{3}{2}T_m\right) + (1-p_d)(\tau + T_d))P_r \tag{6.9}$$

Consequently, the above energy for a failed single transmission is like:

$$e_{fail}^{r} = p_m\left(\tau + \frac{3}{2}T_m\right)P_r + (1-p_m)\left(\tau + \frac{3}{2}T_m\right)P_r + p_d(\tau + T_d)P_r \tag{6.10}$$

However, there are *N* "eligible" receiver nodes. Therefore, we consider different cases in which *i* nodes ($i \le N$) successfully receive the packet without error. The average energy consumed in a single transmission in all possible cases is:

$$e^r_{Nsucc} = \frac{\sum_{i=1}^{N}[\binom{N}{i}(ie^r_{succ} + (N-i)e^r_{fail})]}{\sum_{i=1}^{N}\binom{N}{i}} \tag{6.11}$$

If all the nodes fail to receive the packet without error, the energy consumed in a single transmission is:

$$e^r_{Nfail} = N.e^r_{fail} \tag{6.12}$$

6.3.3. Adaptive PS-MAC

In case of one sender and one receiver when $L_{pr} = CI$, the probability that the receiver wakes up and catches a micro frame is $\frac{L_{pr}}{CI}$. Nevertheless, in case of one sender with preamble size of L_{pr} and *N* receiver nodes with checking intervals of $CI_1 = CI_2 = \cdots = CI_N = CI \neq L_{pr}$ the probability that at least one sender wakes up and detects a micro frame is as follows:

$$p_{detetion} = 1 - \left(1 - \frac{L_{pr}}{CI}\right)\ldots\left(1 - \frac{L_{pr}}{CI}\right) = 1 - \ (1 - \frac{L_{pr}}{CI})^N \tag{6.13}$$

If *N* receivers have different *CI* independent from each other, the above probability will be:

$$p_{detetion} = 1 - \left(1 - \frac{L_{pr}}{CI_1}\right)\left(1 - \frac{L_{pr}}{CI_2}\right)\ldots\left(1 - \frac{L_{pr}}{CI_N}\right) = 1 - \prod_{i=1}^{N}(1 - \frac{L_{pr}}{CI_i}) \tag{6.14}$$

ap-MAC

In ap-MAC protocol, the sender node adapts its preamble length to $L'_{pr} \leq L_{pr}$ that contains $r'_m = \left\lceil \frac{L'_{pr}}{T_m} \right\rceil$ micro frames ($r'_m \leq r_m$). All receiver nodes have equal *CI* values that $CI \geq L'_{pr}$. Therefore, the probability that one node detects the preamble is $\frac{r'_m}{r_m}$. Since $CI \geq L'_{pr}$ the number of receivers that can detect the preamble will drop to $M \leq N$, where M can be calculated as:

$$M = \frac{r'_m}{r_m} N \tag{6.15}$$

The probability of failure for a single transmission will remain the same as RB-MAC in **eq. (6.6)**. Energy drained in transmitter in successful and failed single transmission are as follows:

$$e^t_{succ} = e^s + \big((1 - p_m)(r'_m T_m) + (1 - p_d)T_d\big)P_t \tag{6.16}$$

$$e^t_{fail} = e^s + p_m(r'_m T_m)P_t + \big((1 - p_m)(r'_m T_m) + p_d T_d)\big)P_t \tag{6.17}$$

The energy drained in a receiver node in a successful/failed single transmission is the same as RB-MAC eq. (6.9) / eq. (6.10) respectively. However, with M out of N receiver nodes that detect the preamble, energy consumed in single successful transmission would be similar to eq. (6.11) and is written as:

$$e^r_{Msucc} = \frac{\sum_{i=1}^{M}[\binom{M}{i}(ie^r_{succ} + (M - i)e^r_{fail})]}{\sum_{i=1}^{M}\binom{M}{i}} \tag{6.18}$$

Likewise, the energy consumed in a single transmission with failure in all nodes would be:

$$e^r_{Mfail} = M.e^r_{fail} \tag{6.19}$$

as-MAC

In as-MAC protocol, the preamble size in sender node is L_{pr} and all receivers have $CI_i \neq L_{pr}$. The *CI* value for each node is independent from other nodes and has a length of r_i times of a micro-frame ($r_i = \left\lceil \frac{CI_i}{T_m} \right\rceil$) whereas $r_m \leq r_i \leq r_{max}$.In addition r_m and r_{max} corresponds to L_{pr} and CI_{max} respectively.

The probability that one node detects the preamble is $\frac{r_m}{r_i}$. *V* represents the number of receivers that are successful in preamble detection (*V* ≤ *N*). *V* is formulized as:

$$V = \sum_{i=1}^{k} V_i = \sum_{i=1}^{k} (\frac{r_m}{r_i}) N_i \qquad (6.20)$$

$$1 \leq i \leq k$$

where k is the groups of nodes with the same *CI* and N_i is the number of nodes with $CI_i = r_i T_m$. In as-MAC the preamble size is the same is RB-MAC, therefore; p_f, e_{succ}^t and e_{fail}^t can be achieved by the same equations as (6.6), (6.7), and (6.8) respectively.

The energy drained in a receiver node in a successful/failed single transmission is equal to RB-MAC eq. (6.9) / eq. (6.10) respectively. However, for *V* out of *N* nodes detecting the preamble, the energy consumed in a single transmission is:

$$e_{Vsucc}^r = \frac{\sum_{i=1}^{V} [\binom{V}{i} (i e_{succ}^r + (V - i) e_{fail}^r)]}{\sum_{i=1}^{V} \binom{V}{i}} \qquad (6.21)$$

Finally the energy consumed in a single transmission with failure in all nodes would be:

$$e_{Vfail}^r = \mathrm{V}.\, e_{fail}^r \qquad (6.22)$$

6.4. Numerical Results

6.4.1. Simulation Environment

We compare the performance of our proposed protocols against SB-MAC and RB-MAC in terms of energy consumption, lifetime and reliability. *n* is the predefined maximum number of retransmission (i.e. *n=7).*

The simulation results have been achieved in MATLAB. We utilize the CC2500 [CC2500] characteristics with the micro-frame length of 16 bytes and control frame length of 128 bytes. The number of receivers *N* is equal to 10. In SB-MAC, we consider $T_{CW} = 30\ \mathrm{ms}$ for collision probability of less than 10% according to [14]. **Table 6-2** shows the current consumption of the CC2500 which uses the voltage supply of 3V and **Table 6-3** shows the symbols and their value used in the numerical results.

Table 6-2 Features of CC2500 [CC2500]

Mode	Symbol	Current Consumption
Transmit at 0dBm	*Tx*	21.2 mA
Receive	*Rx*	14.5 mA
Idle	*Ix*	1.5 mA
Sleep	*Sx*	900 nA

Table 6-3 Symbols for the analysis

τ = 88.4 (µs)	Transition from sleep to active mode
f = m/DR	Active part of a MF
s = 52 (µs)	gap between two MFs
Tm = f + s	Duration of one MF
Td = 4 (ms)	Duration of Data
V = 3 volts	Voltage of battery

6.4.2. Energy Consumption

In this subsection, we will try to compare the performance of proposed protocols in terms of energy consumption. We plot the total consumed energy in one packet transmission. As we consider up to n times retransmission by the sender node, the energy drained in one transmission E_t will depends of the probability of success/failure and e_{succ}^t / e_{fail}^t in a single transmission. Therefore:

$$\begin{aligned} E_t &= (1-p_f)e_{succ}^t + (1-p_f)p_f\left[e_{fail}^t + e_{succ}^t\right] + \cdots \\ &\quad + (1-p_f)p_f^{n-1}\left[(n-1)e_{fail}^t + e_{succ}^t\right] + p_f^n n e_{fail}^t \\ &= \frac{1-p_f^n}{1-p_f}\left(p_f e_{fail}^t + (1-p_f)e_{succ}^t\right) \end{aligned} \tag{6.23}$$

E_r energy drained in receiving mode can be calculated by replacing e_{succ}^t and e_{fail}^t by e_{succ}^r and e_{fail}^r accordingly in the above equation. The total energy consumption of a sender node and *N* receiver(s) are calculated for variable bit error rates (BER). **Figure 6-4** illustrates the growth in total energy consumption for all protocols as the BER increases. In channels with rather low BER, RB-MAC, SB-MAC and as-MAC have almost equal but higher energy consumption than ap-MAC. The gap between the former three protocols and ap-MAC widens with worse channel conditions. The total energy consumption remains flat when it reaches a particular point in BER. This is due to the fact that number of retransmission (*n)* reaches its maximum value.

In very poor channel conditions, the worst energy performance belongs to RB-MAC because sender node transmits full-sized preamble and all *N* receivers are involved in receiving data with several retransmissions. However, as-MAC shows slightly better energy savings than RB-MAC and SB-MAC. With a lower preamble length, ap-MAC implies the best energy savings among all the MACs. This is achieved because shorter preamble size considerably reduces total transmission energy consumptions. This also reflects the fact that in all protocols a larger portion of energy is consumed in sender nodes.

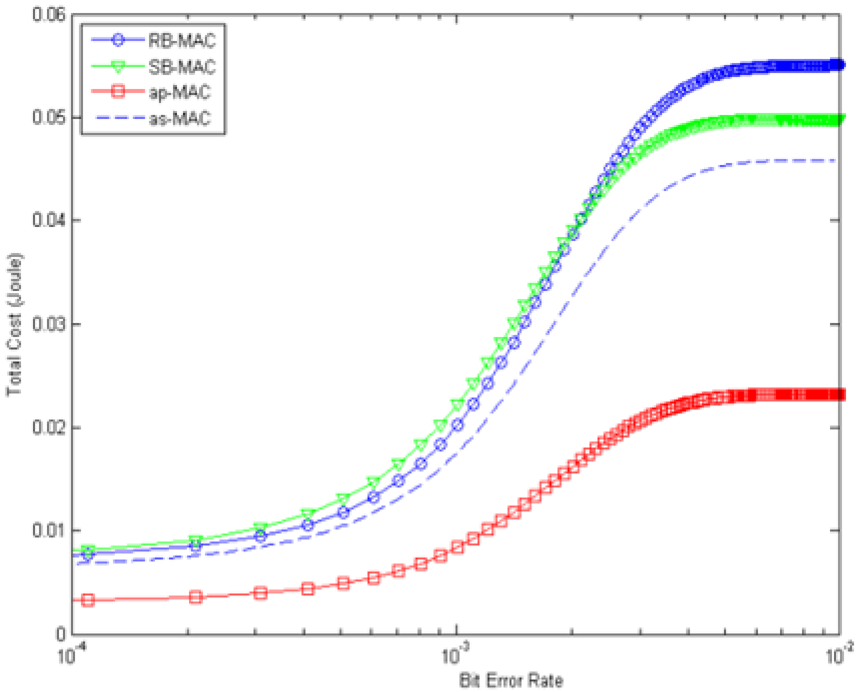

Figure 6-4 Total Energy Consumption

6.4.3. Lifetime

We draw normalised lifetime (in seconds) of nodes in relation to the mentioned protocols in **Figure 6-5**. We assume lifetime of a node in each protocol as $L = \frac{E_{initial}}{P_o}$ were $E_{initial}$is the initial energy of a node and P_o (Joule/sec) is the average power of a node consumed in transmission, reception and channel sampling. We consider a traffic load of one message every five minutes. The noticeable result is that ap-MAC implies a better lifetime of up to two times. This is achieved because a shorter preamble is used in ap-MAC in comparison with other protocols. In as-MAC as *CI* values in receivers are longer than preamble length, the probability of detection of the preamble and consequently receiving the data are reduced. Spending less time in receiving and forwarding, as-MAC makes the node's lifetime performance better than SB-MAC and RB-MAC.

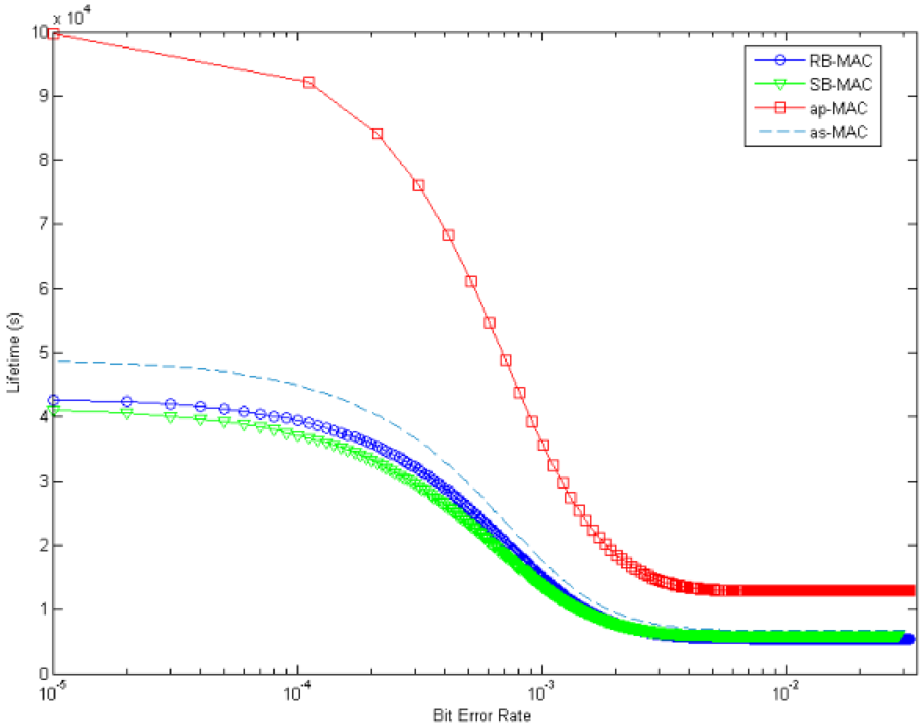

Figure 6-5 Normalized Lifetime

6.4.4. Reliability

We define p_f to be the probability that a single transmission fails. The reliability is defined as the probability of successfully delivering the data to the receiver(s). For the SB-MAC, reliability is:

$$R_{SB-MAC} = 1 - p_f^n \tag{6.24}$$

However, we expect that RB-MAC improves reliability since there is more than one eligible neighbour node. Considering N receiver nodes, failure probability drops to p_f^N and reliability grows to a better value of:

$$R_{RB-MAC} = 1 - p_f^{nN} \tag{6.25}$$

The same approach is applied for ap-MAC and as-MAC while replacing N with the number of receivers participating in the data transfer process.

Figure 6-6 illustrates reliability of the previously described protocols. As expected, SB-MAC (relying on only one node as receiver) has the lowest reliability while RB-MAC with engaging all the receivers provides the most reliable protocol. Interestingly ap-MAC with shorter preamble $(L'_{pr} = 0.4CI)$ offers almost the same level of reliability as RB-MAC. This is because the number of receivers in ap-MAC with considering node density is enough to provide the same level of reliability. This result shows that, we can save more than half of the transmission power of RB-MAC without losing any reliability.

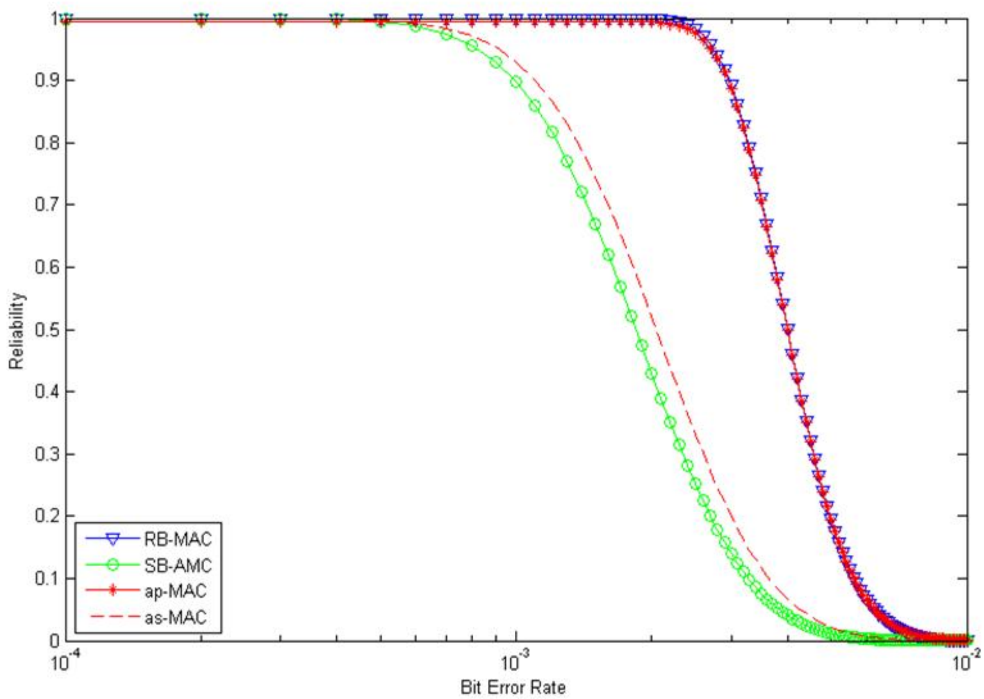

Figure 6-6 Reliability of data delivery

6.5. Conclusions

Preamble sampling (PS-) MAC protocols save considerable amount of energy especially in low traffic applications. In existing PS-MACs, sensor nodes sample the channel every *CI* that is equal to the preamble length. In this work, we consider a WSN in which there is more than one receiver node. We proposed and evaluated adaptability of preamble and checking intervals. Firstly, we introduced ap-MAC protocol, in which preamble length has been shortened by the sender node to save further energy. This reduces the probability of detecting the preamble by receivers but saves energy in receivers. Secondly, we introduced as-MAC protocol that employs variable *CI* values in receiver nodes. Performance evaluation using analytical models and simulation runs show that ap-MAC provides an equal level of reliability as RB-MAC without increasing energy consumption. In addition, as-MAC increases lifetime of the network depending on the amounts of *CI* that receiver nodes apply. We have shown by analysis that the proposed adaptive PS-MAC outperforms the state-of-the-art sender-based and receiver-based preamble sampling MAC protocols. The next chapter will focus on utilising the proposed MAC protocols in multi-hop routing protocols.

7. Multi-hop Performance of RB-MAC in RPL

7.1. Introduction

In the communication stack, MAC layer supports the routing protocols, enabling communication between neighbours, and by obtaining link & node level data such as energy-efficiency, link reliability, etc. The routing protocol uses these data to discover multi-hop traversing different nodes in the network; some of these paths may need to provide a certain level of Quality-of-Service (e.g. the most energy efficient path using only links with a packet delivery ratio higher than 95%). In addition, this may require a data-forwarding algorithm suitable for heterogeneous wireless sensor networks consisting of sensors with different powering mechanisms and different energy-levels. For example, a path involving more solar-powered sensors with a higher energy-harvesting rate is preferred to a path consisting of sensors with non-rechargeable batteries. For example, in **Figure 7-1** different paths from node A to the sink can be used depending on routing metrics. This can be provisioned as the optimisation function for the protocol to operate.

When a node is forwarding a packet, RB-MAC dynamically elects the next-hop node among a number of potential relay neighbours, based on current channel conditions. Because RB-MAC *elects* reliable links, it reduces the number of retransmissions. This increases end-to-end reliability and energy efficiency, and decreases delay [Bis05]. Note that RB-MAC participates in the forwarding process, resulting in a cross-layered approach (using MAC layer information for routing and forwarding). Without loss of generality we assume RPL as the routing protocol operating in the network. As stated, unlike previous works noted in section **5.3**, our aim is to apply our receiver-based technique to the state-of-the-art RPL rather than geographic or tree-based routing protocols although RB-MAC can be applied to any gradient based routing protocols (including geographic routing protocols). This results in a cross-layer approach in which routing decisions can be made based on MAC-layer functionalities.

As described in Chapter 3, the IETF's ROLL working group recently proposed RPL as a standard routing protocol for LLNs [RFC6550]. Unlike tree-based topologies, RPL builds a Directed Acyclic Graph (DAG) in which paths are created from nodes towards the root. These are called Destination Oriented DAGs, or DODAGs. A DODAG offers redundant paths to increase reliability of the network. If topology permits, there is always more than one path from each leaf node to the DODAG root [Vas10]. This is an important driver for us in proposing RB-MAC to support RPL, as each node has at least two neighbour nodes.

The goal of this chapter is to investigate the performance of RB-MAC and adaptive RB-MAC in multi-hop routing such as RPL. The effects of adaptive preamble and adaptive duty cycling in end-to-end reliability, delay and energy-efficiency have been studied. Results are obtained from analytical models and supported by simulation runs and numerical solutions using features of the CC2500 wireless module.

In the rest of this chapter, we first investigate the performance of RB-MAC and adaptive RB-MAC in single-hop and extend the results for a multi-hop scenario by natively taking into account the lossy nature of the wireless links.

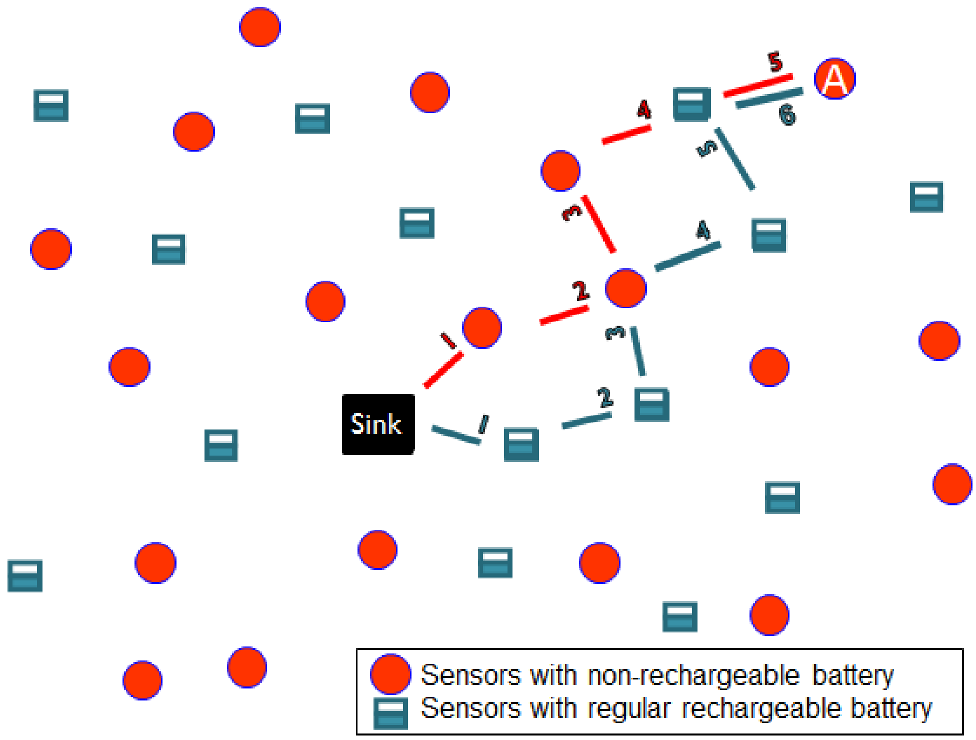

Figure 7-1 Energy-aware routing in heterogeneous WSN

7.2. Model for retransmissions

To calculate multi-hop performance, we need to analyse it for a single hop. Since delay, energy and reliability are directly related to packet retransmission probability, it is important to have a suitable model for retransmissions.

With retransmission node tries to send data to the next node in the case of a failed transmission. Each protocol considers a maximum threshold for the number of retransmissions denoted by *Z*. Hence, *i* data transmissions (packets) happens in a single hop to send data successfully which $0<i\leq Z$. After *Z* retransmissions the data packet will be dropped.

For the rest of our calculations, we use the weighted average of possible values of the number of retransmissions which is the expected value of this parameter.

The probability of failure for a single transmission is dependent on the probability of corruption in preamble or data frame, is thus given by

$$P_f = 1 - (1-p)^{m+d} \tag{7.1}$$

where p denotes bit error probability.

Let P_i denote the probability that node will successfully transmit the packet after *i* failures. Thus, P_i is given by

$$P_i = \left(P_f\right)^i (1 - P_f) \tag{7.2}$$

Let i be the random variable that represents the total number of retransmissions until success. Since P_i represents the Probability Mass Function (PMF) of i, the average number of retransmissions until success can be calculated as follows:

$$N_t = Exp(n) = \sum_{i=0}^{\infty} i\, P_i = \frac{P_f}{1 - P_f} \tag{7.3}$$

where $Exp(n)$ denotes the expected value. However, in practice, there is a limit on the maximum number of retransmissions. Assuming that the maximum number of retransmissions is Z, the probability of packet drop is given by $P_{drop} = P_f{}^{Z+1}$.

7.3. Average number of retransmissions for SB-MAC

When there is one sender and one receiver nodes, the expected value of number of retransmission is:

$$\begin{aligned} Exp(n)_{SB-MAC} &= \sum_{i=0}^{Z} iP_i + (Z+1)P_f^{(Z+1)} \\ &= \left(\sum_{i=0}^{Z} iP_f^i\left(1 - P_f\right)\right) + ZP_f^{(Z+1)} \\ &= \frac{P_f - (Z+1)P_f^{(Z+1)} + ZP_f^{(Z+2)}}{\left(1 - P_f\right)} + ZP_f^{(Z+1)} \end{aligned} \tag{7.4}$$

The multiplying factor should be $(Z+1)$ instead of *N* as the *(Z+1)*th transmission is dropped with probability P_f^{Z+1}. In which P_f implies the probability of failure of a single transmission, $P_f = 1 - (1-p)^{m+d}$ and P_i represents the probability of *i* retransmissions, $P_i = P_f^i\left(1 - P_f\right)$.

7.4. Average number of retransmissions for RB-MAC

In RB-MAC, *N* receiver nodes receive the data from a sender. In this protocol when at least one of the receivers successfully receives data, the sender stops retransmitting data. Intuitively, this reduces the number of retransmission in each hop. Let P_L shows the probability that at least one receiver successfully receives the data:

$$P_L = 1 - P_f^N \tag{7.5}$$

and with *N* receivers, the probability of data transmission after I failure changes to:

$$P_i = (P_f^N)^i\left(1 - P_f^N\right) \tag{7.6}$$

$$\begin{aligned} Exp(n)_{RB-MAC} &= \sum_{i=0}^{Z} iP_i \\ = \sum_{i=0}^{Z} iP_f^{Ni}\left(1 - P_f^N\right) &+ ZP_f^{NZ}P_f \\ = \frac{P_f^N - (Z+1)P_f^{N(Z+1)} + ZP_f^{N(Z+2)}}{\left(1 - P_f^M\right)} &+ ZP_f^{NZ+1} \end{aligned} \tag{7.7}$$

Figure 7-2 illustrates the average number of retransmissions in a single hop for SB-MAC and RB-MAC with 10 receiver nodes. As expected, RB-MAC shows more robust features as it starts to retransmit data in the worst channel conditions. The reason that RB-MAC has sharp increase in comparison to SB-MAC is, in SB-MAC retransmission depends of only one receiver's failure in forwarding the packet. However, in RB-MAC retransmission will not starts unless all of the receivers fail to forward the packet. Therefore, RB-MAC is more resilient to SB-MAC. However, RB-MAC's retransmission cost is the same as the SB-MAC.

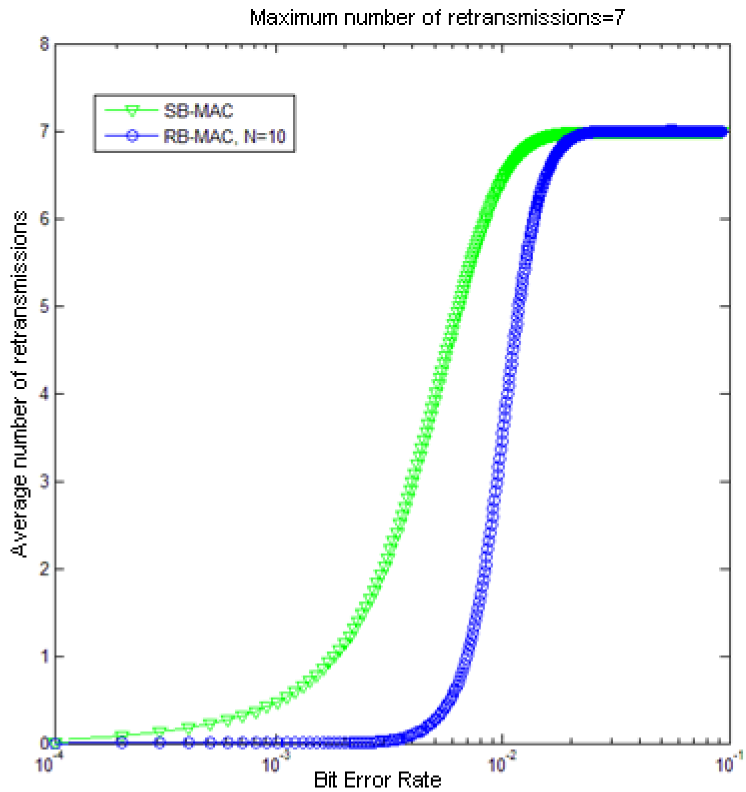

Figure 7-2 average number of retransmissions for SB-MAC and RB-MAC

7.5. Average number of retransmissions for ap-MAC

As explained in section 6.2, ap- and as-MAC are subset of RB-MAC protocol in which the number of receivers has been limited by different mechanisms. In ap-MAC, when a sender node shorten its preamble size, the number of nodes in sender's communication range will be decreased because some nodes may not be able to detect the short preamble due to their larger CI value. Therefore, we consider M as the number of receivers in ap-MAC which is $1 \leq M \leq N$. *N* is the number of receiver nodes in RB-MAC and average of *M* is equal to $(N+1)/2$. Therefore, the average number of retransmission for as-MAC is given by:

$$
\begin{aligned}
Exp(n)_{ap-MAC} &= \sum_{i=0}^{Z} iP_i \\
&= \sum_{i=0}^{Z} iP_f^{Mi}\left(1-P_f^M\right) + ZP_f^{MZ}P_f \\
&= \frac{P_f^M - (Z+1)P_f^{M(Z+1)} + ZP_f^{M(Z+2)}}{\left(1-P_f^M\right)} + ZP_f^{MZ+1}
\end{aligned}
\tag{7.8}
$$

7.6. Average number of retransmissions for as-MAC

In as-MAC, the receiver nodes may enlarge their *CI* value, consequently the probability of detecting the preamble decreases. If we assume the potential number of receivers in as-MAC is *V*, where $1 \leq V \leq N$, For average of $V = Exp(V) = \sum_{j=0}^{N} jP_{detection,j} = \sum_{j=0}^{N} j\frac{L_{pr}}{CI_j}$, the average number of retransmission for as-MAC is given by:

$$
\begin{aligned}
Exp(n)_{as-MAC} &= \sum_{i=0}^{Z} iP_i \\
&= \sum_{i=0}^{Z} iP_f^{Vi}\left(1-P_f^V\right) + ZP_f^{VZ}P_f \\
&= \frac{P_f^M - (Z+1)P_f^{V(Z+1)} + ZP_f^{V(Z+2)}}{\left(1-P_f^V\right)} + ZP_f^{VZ+1}
\end{aligned}
\tag{7.9}
$$

7.7. Multi-hop Delay

Assuming that the delay associated with a single hop transmission is given by D_{SH} ,and all nodes introduce the same transmission delay, which includes the transmission and propagation delays, the end-to-end delay over h hops is given by:

$$D_h = h \times D_{SH} \tag{7.10}$$

In the next sub-sections, we will calculate single hop delay in different protocols. We assume that all nodes introduce the same transmission delay in multi-hop network and all single hops have the same characteristics (same BER).

7.7.1. Single-hop delay in SB-MAC

$$D_{SB-MAC} = (L_{pr} + T_{CW} + T_d) \times Exp(n)_{SB-MAC} \tag{7.11}$$

7.7.2. Single-hop delay in RB-MAC

$$D_{RB-MAC} = \left(L_{pr} + T_d + \frac{T_{CW}}{2}\right) \times Exp(n)_{SB-MAC} \tag{7.12}$$

7.7.3. Single-hop delay in ap-MAC

$$D_{ap-MAC} = [average(L'_{pr}) + T_d + T_{CW}/2] \times Exp(n)_{ap-MAC} \tag{7.13}$$

where $\frac{L_{pr}}{N} \leq L'_{pr} \leq L_{pr}$. The minimum value for L'_{pr} is $\frac{L_{pr}}{N} \leq L'_{pr}$ this is to ensure at least one receiver nodes in communication range detect the preamble and average of $\left(L'_{pr}\right) = \frac{N+1}{2N} L_{pr}$.

Therefore the single hop delay for ap-MAC would be:

$$D_{ap-MAC} = \frac{N+1}{2N} L_{pr} + T_d + T_{CW}/2 \tag{7.14}$$

7.7.4. Single-hop delay in as-MAC

$$D_{as-MAC} = (L_{pr} + T_d + T_{CW}/2) \times Exp(n)_{as-MAC} \quad (7.15)$$

Figure 7-3 demonstrates as the multi-hop delay performance of RB-MAC improves as the number of neighbours increases. In other words, as the number of receivers in RB-MAC increase, the probability of reception among the node increases. This causes fewer retransmissions and consequently delay reduces.

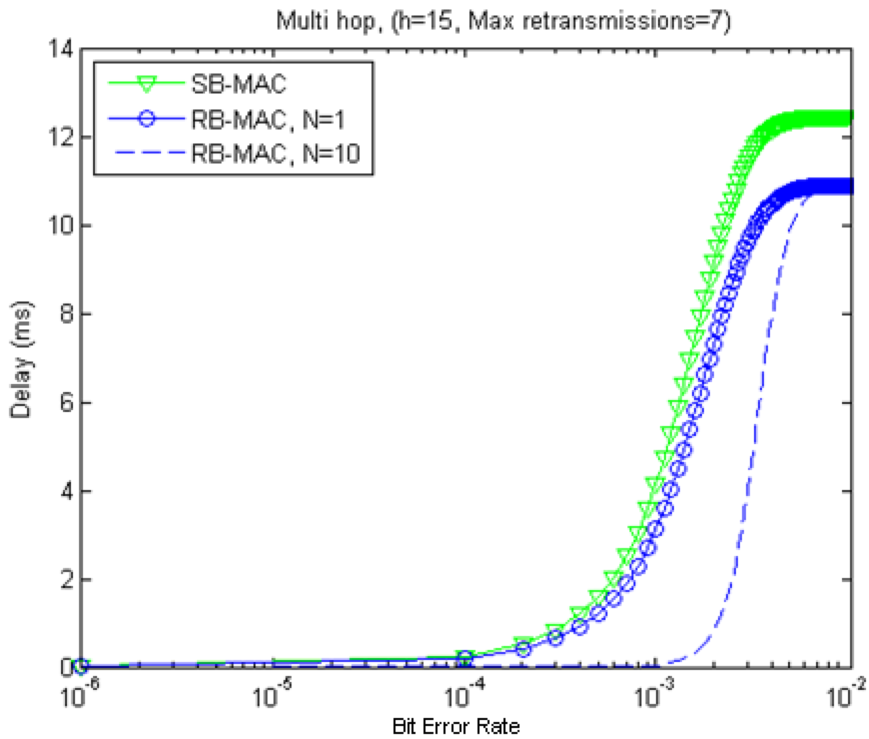

Figure 7-3 Multi-hop delay in RB-MAC with different receivers (*h*=15, *N*=10)

Figure 7-4 shows delay performance of ap-MAC in multi-hop mode is much better than RB-MAC and as-MAC. This is because in ap-MAC the size of preamble has been decreased; this is an extra advantage over RB-MAC or as-MAC which is only relay on multiple reception of the packet and fewer retransmissions.

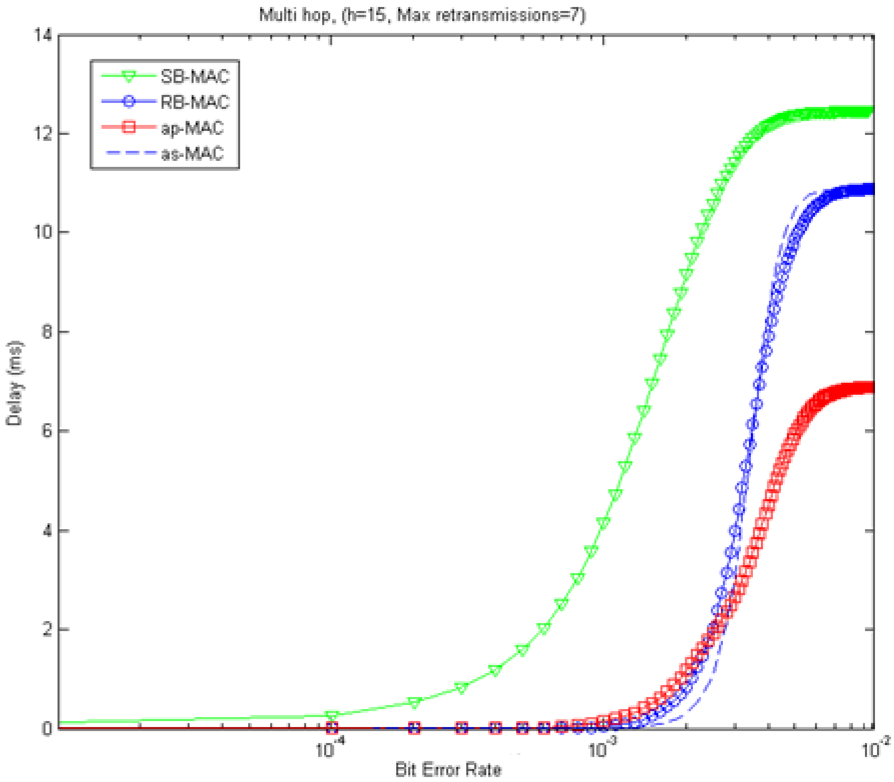

Figure 7-4 Multi-hop delay performance of RB-MAC, ap-MAC and as-MAC

7.8. Multi-hop Energy

Consider there are h hops between a sender and the sink node. In each single hop, the transmitter/receiver energy consumptions are shown by e^t and e^r respectively. Therefore, the multi-hop energy consumption can be expressed by:

$$E_{MH} = h \times e^t + (h-1) \times e^r \tag{7.16}$$

where

$$e^t = \frac{1 - p_f^{Exp(n)+1}}{1 - p_f}\left(p_f e^t_{fail} + (1 - p_f) e^t_{success}\right) \tag{7.17}$$

$$e^r = \frac{1 - p_f^{Exp(n)+1}}{1 - p_f}\left(p_f e^r_{fail} + (1 - p_f) e^t_{success}\right) \tag{7.18}$$

By using relevant expressions for $Exp(n)$, $e^t_{success}$, e^t_{fail} , $e^t_{success}$, and e^r_{fail} for SB-MAC, RB-MAC, ap-MAC and as-MAC the following results have been achieved.

Figure 7-5 shows how much each of the SB-MAC and RB-MAC protocols consumes energy for different channel conditions. We see that RB-MAC spends less energy than SB-MAC when number of receivers is one. This is because number of retransmissions is less for RB-MAC. In the case where the number of receivers is increased to 10 the probability that at least one receiver successfully gets data is increased. That is why RB-MAC is more resilient to the variations in channel quality longer than that of SB-MAC and RB-MAB with one receiver. However, the overall energy consumed in saturated mode (when the number of retransmissions reaches 7) shows that RB-MAC consumes more energy than the two before aforementioned schemes.

Figure 7-6 shows ap-MAC outperforms as-MAC and RB-MAC in multi-hop energy-efficiency. This is due to the fact that by reducing the long preamble size energy has been saved. Energy performance of as-MAC is almost the same as SB-MAC as lower BER. However, as the lossyness of the channel increases the role of multiple receivers highlights and ap-MAC outperform SB-MAC.

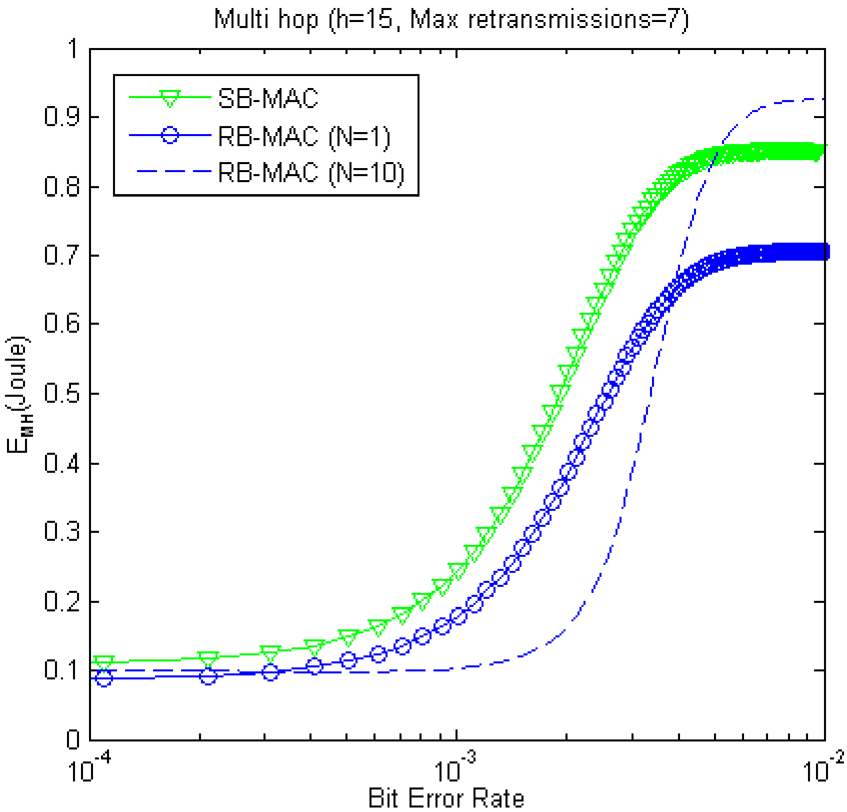

Figure 7-5 Multi-hop energy performance of RB-MAC (h=15, N=10)

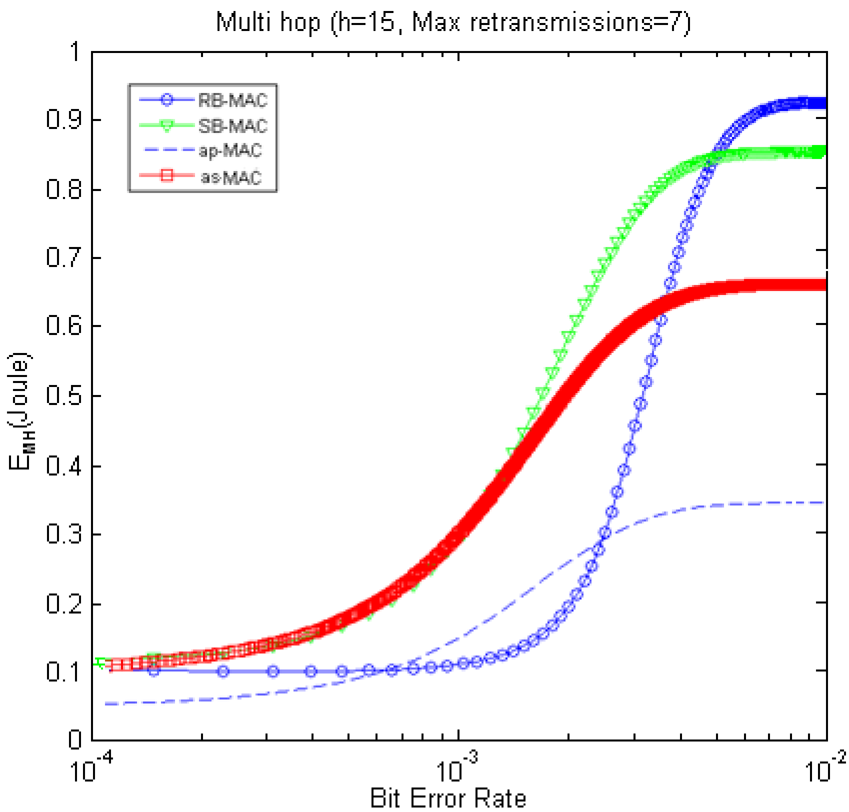

Figure 7-6 Multi-hop energy performance of RB-MAC, ap-MAC and as-MAC

7.9. Multi-hop Reliability

Similar to multi-hop energy, we can follow similar approach to calculate the reliability of different protocols in multi-hop scenario. If *R* represents the reliability of a single-hop data transmission, and if we assume that all nodes introduce the same level of reliability, then the calculation for multi-hop reliability is as follows:

$$R_{MH} = R^h \tag{7.19}$$

Where h is the number of hops. The average the single-hop reliability in SB-MAC, RB-MAC, ap-MAC and as-MAC are as follows:

$$R_{SB-MAC} = 1 - P_f^{(Exp(n)_{SB-MAC}+1)} \tag{7.20}$$

$$R_{RB-MAC} = 1 - P_f^{(Exp(n)_{RB-MAC}+1)N} \tag{7.21}$$

$$R_{ap-MAC} = 1 - P_f^{(Exp(n)_{ap-MAC}+1)M} \tag{7.22}$$

$$R_{as-MAC} = 1 - P_f^{(Exp(n)_{as-MAC}+1)V} \tag{7.23}$$

where N, M, and V are the number of receivers in RB-MAC, as-MAC, and as-MAC respectively. By replacing the relevant $Exp(n)$ with Z in the above equations, we can get the reliability of the protocols in with maximum number of retransmission:

$$R'_{SB-MAC} = 1 - P_f^{Z} \tag{7.24}$$

$$R'_{RB-MAC} = 1 - P_f^{ZN} \tag{7.25}$$

$$R'_{ap-MAC} = 1 - P_f^{ZM} \tag{7.26}$$

$$R'_{as-MAC} = 1 - P_f^{ZV} \tag{7.27}$$

Figure 7-7 shows that reliability of RB-MAC is highest among other protocols. This is because more nodes are involved in receiving the packet. As expected ap-MAC and as-MAC reliabilities are somewhere re located between SB-MAC and RB-MAC.

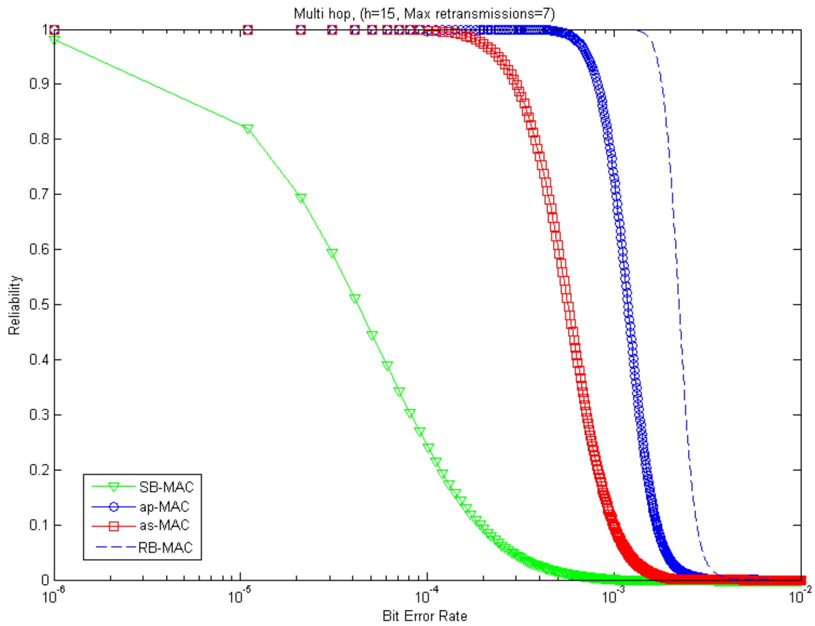

Figure 7-7 Multi-hop reliability performance of RB-MAC, ap-MAC, and as-MAC

7.10. Simulation Analysis

7.10.1. Simulation Environment

In this section, we evaluate the multi-hop performance of SB-MAC and RB-MAC using MATLAB based simulation runs. Without loss of generality, we assume that RPL is operating as routing protocol. We consider a single RPL instance with one DODAG whereby nodes are randomly distributed according to Poisson distribution with a certain density as shown in **Figure 7-8** (where the ranks of each node are also displayed). The ranks are assigned according to the distance from the DODAG root, which is node 0 in our case. We run a time-driven simulation whereby the transmitting nodes are randomly selected at various instances throughout the simulation and average results are obtained at the end. We assume 1) a fading channel between any two nodes where the channel fading amplitude is Rayleigh distributed 2) instantaneous channel values are averaged out over 100 instances, 3) the multi-hop performance values are further averaged over 5 instances in each scenario.

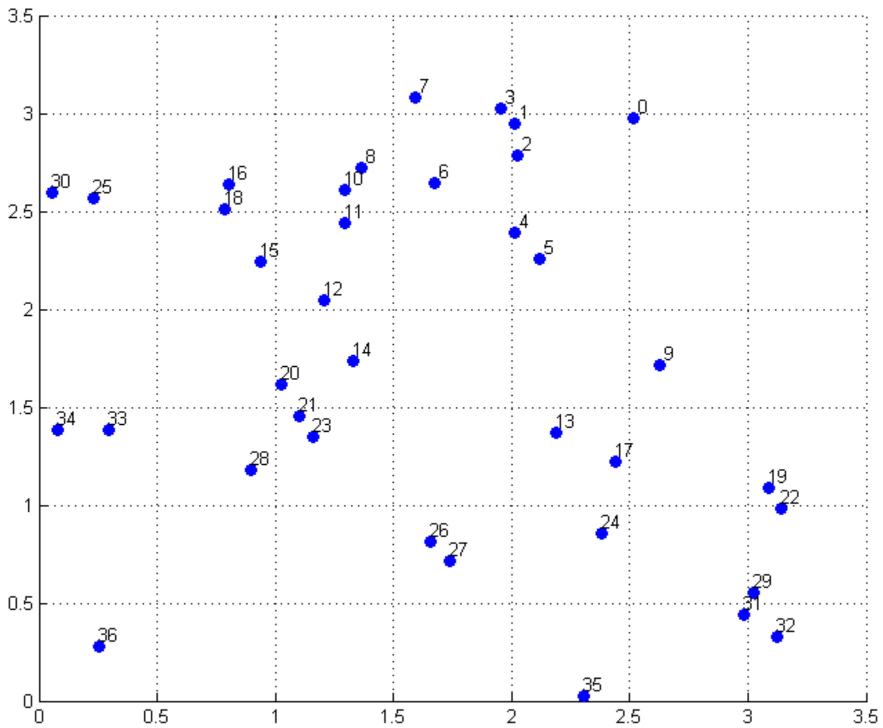

Figure 7-8 A sample simulated topology with Poisson distributed node locations (area = 10 sq units, density = 3 nodes per unit area). The node ranks are displayed whereby node 0 serves as the sink.

7.10.2. Simulation Results

We evaluated the performance in terms of number of re-transmissions occurred for the end-to-end transmission of a single packet over multiple hops. The simulation results can be directly mapped to energy or delay performance, as shown in analytical modelling for energy and delay over multiple hops. The multi-hop performance comparison of SB-MAC and RB-MAC (for different number of receivers), and as-MAC and ap-MAC are shown in **Figure 7-9** and **Figure 7-10**.

The channel state characterization in terms of 'good' and 'poor' is based on the outage probability calculations for a Rayleigh fading channel as described in Appendix A.

Figure 7-9 presents a comparison of the performance of different protocols in terms of average number of retransmissions required for a successful end-to-end transmission. We assume a Rayleigh fading channel between two nodes and the channel characterisation is in terms of outage probability between any two nodes. Specifically, the 'good' channel refers to an outage probability of 0.1 whereas a 'poor' channel refers to an outage probability of 0.4. From the results shown in **Figure 7-9**, we note that over good channel conditions, the performance of different protocols is not much different. However, under poor channel conditions, there is significant improvement by using RB-MAC and its variants over the SB-MAC. As the number of receivers for RB-MAC increases, the number of retransmissions reduces due to the additional available receivers. We also compare the performance of ap-MAC and as-MAC for different preamble lengths and checking intervals. For ap-MAC reducing the preamble duration degrades the performance compared to RB-MAC as fewer receivers can successfully detect and hence act as potential forwarders. With a similar reasoning for as-MAC, reducing the check interval duration degrades the performance compared to RB-MAC. Interestingly, if we consider the ratio of reduction in preamble length of ap-MAC to be the same as the ratio of increasing checking interval in as-MAC, the number of potential receivers that can detect the sender's preamble would be the same. Therefore, the number of retransmissions in ap-MAC ($L' = L/3$) is almost the same as that of as-MAC $(CI = L_{pr}/3\,)$, equal to the number of retransmissions of RB-MAC with two receivers. Based on the values given in **Table 6-2**, we also calculated the energy required for successful end-to-end transmission as shown in **Figure 7-10**. By comparing **Figure 7-9** and **Figure 7-10**, one can conclude that although the number of receivers capable of detecting sender's preamble in ap-MAC $(L' = L/3\,)$ is the same as as-MAC $(CI = L/3\,)$ and both have almost the same number of retransmissions, energy performance of ap-MAC is much better than that of as-MAC. This is due to shorter preamble lengths used in ap-MAC. Meanwhile, energy performance of as-MAC $(CI = L/3\,)$ is the same as energy performance of RB-MAC (*NR=2)*. This is because of an equal size of preamble used in as-MAC and RB-MAC.

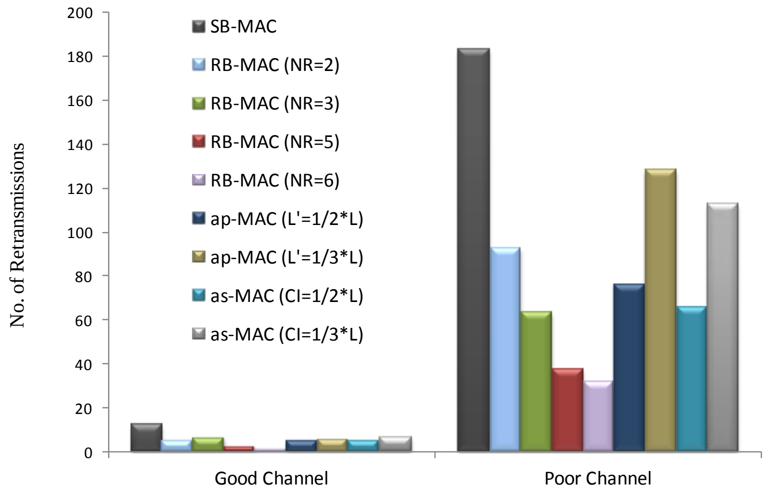

Figure 7-9 Simulation results for different protocols. Performance is evaluated over a Rayleigh fading channel (results are averaged over 5 iterations). In ap- and as- MACs, NR is equal to 6.

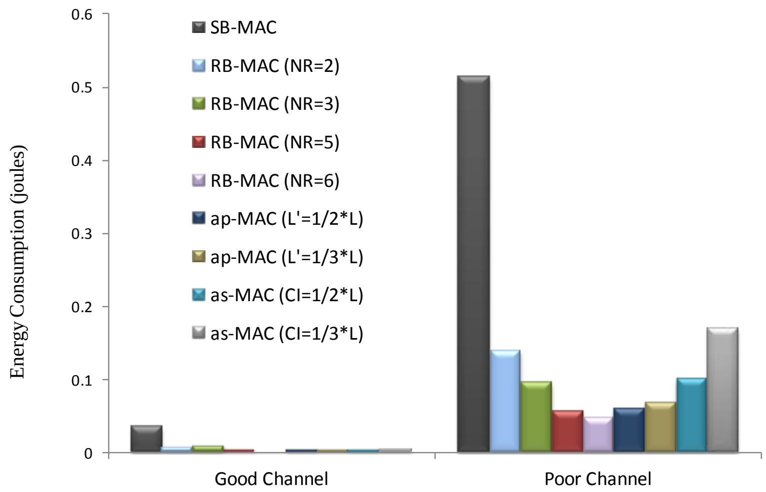

Figure 7-10 Simulation results for different protocols. Performance is evaluated over a Rayleigh fading channel (results are averaged over 5 iterations). In ap- and as- MACs, NR is equal to 6.

7.11. Conclusions

In this chapter, we investigated the performance of RB-MAC and adaptive RB-MAC in multi-hop scenario especially for RPL routing protocol. We introduced a retransmission model for each protocol in a single-hop and then extended to a multi-hop mode. In this model we consider bit error probability and obtained average number of retransmissions until a successful data packet transmission. The expected number of retransmissions for SB-MAC, RB-MAC, ap-MAC and as-MAC are also calculated. We studied the impact of multiple receiver nodes and size of preamble in the performance studies. Retransmissions have direct impact on delay, energy-efficiency and reliability. The results indicate that a sender node with shorter preamble size will consume less energy and transmit its data to the next hop with less delay. Non-sender nodes by choosing longer CI size can save more energy. However, these gains come at the cost of lower reliability as the probability of detection of a data packet decreases by shortening preamble size in the sender or increasing the size of CI in receivers. Moreover, we applied the proposed MAC protocols in RPL routing and evaluated them via simulation study. The overall simulation results match the analytical and numerical results.

8. Experimental Studies

In this chapter, we present the performance of the RB-MAC protocol in terms of transmission delay, and energy efficiency using practical implementation. To implement RB-MAC we have used the Configurable MAC (C-MAC) [Stei10] framework, which allowed us to configure, evaluate the performance of protocols to be executed in real sensor nodes. We first explain the Configurable MAC framework and in the next sections experimental results using real sensor nodes are presented followed by conclusions. Bulk of this chapter has been taken from our joint work presented in [Ste13]. [2]

8.1. Configurable MAC (C-MAC) Framework

C-MAC is a framework of medium access control strategies that can be combined to produce application-specific protocols [Stei10]. It enables application programmers to configure several communication parameters (e.g. synchronization, contention, error detection, acknowledgment, etc.) to adjust and create a protocol instance that fulfil the specific needs of their applications.

C-MAC is realized as component-based architecture explained in [Ste10]. Each activity in the diagrams (e.g. **Figure 8-2**) is executed by a micro-component which can have different implementations. These micro-components alongside with the flow control can be combined to produce application-specific protocols. By using static meta-programming techniques, micro-components representing activities that do not make sense for a certain protocol can be completely removed. When an activity is removed, its inputs are forwarded to the activity targeted by its outputs, still maintaining the original flow semantics.

The use of static meta-programming techniques (e.g. templates, inline functions, and inline assembly) ensures that configurability does not come at expense of performance or code size [Stei10]. In this way, C-MAC's instances are fully customized at compile-time and yield extremely efficient run-time MACs.

[2] In this joint work, the author of this thesis contributed the theoretical model and operational algorithms. The implementations have been provided by the collaborators at Software/Hardware Integration Lab, Federal University of Santa Catarina, Brazil.

8.2. Configuring C-MAC

C-MAC configuration is performed using the same concept of *traits* present in the C++ standard library [Str00]. Traits are parameterized classes whose static constant members describe the properties of a certain type [Fro01]. Using the configuration file, shown in **Figure 8-1**, developers can choose which properties the protocol must possess. When a property is selected, its functionality is included in the protocol. In this way, it is possible to define the protocol behaviour at compile time.

```
// ...
template <> struct Traits<CMAC<Radio_Wrapper> >: public Traits<void>
{
// ...
    enum Synchronization {
        NO_SYNC  = 0,
        PREAMBLE = 1,
        BEACON   = 2,
    };

    static const int SYNC = PREAMBLE;

    enum Preamble_Content {
        DUMMY                  = 0,
        TIME_TO_DATA_AND_RANK = 1,
        DESTINATION_ID         = 2,
    };
// ...
    static const int PREAMBLE_CONTENT = TIME_TO_DATA_AND_RANK;
    static const int PREAMBLE_LENGTH  = 144;
    static const int SLEEPING_PERIOD  = 144;
// ...
    static const bool forward_data_to_sink = true;
    static const int RANK  = 2;
// ...
};
// ...
```

Figure 8-1 Traits configuration file.

Figure 8-2 presents the C-MAC activity diagram for B-MAC [Pol04] (as a representative example of sender-based preamble-sampling MAC) and RB-MAC configurations. Only states that are actually used are present. Therefore, there is no additional overhead to the generated code. Both B-MAC and RB-MAC use the same states. However, they use different micro-components to handle preamble synchronization and to determine if a transmission was successful.

8.3. Experimental Results

In order to evaluate RB-MAC in real sensor nodes we chose to use the EPOSMote II, which is an easy to develop and low cost platform with an open hardware project [LISHA]. It's hardware is designed as a layered architecture composed by a main module(responsible for processing, storage, and communication), a sensoring module, and a power module. The node used in this research features a 32-bit ARM7 processor, 128kB of flash, 96kB of RAM, and an IEEE 802.15.4-compliant radio transceiver. **Figure 8-3** shows the development kit which is slightly larger than a R$1 coin.

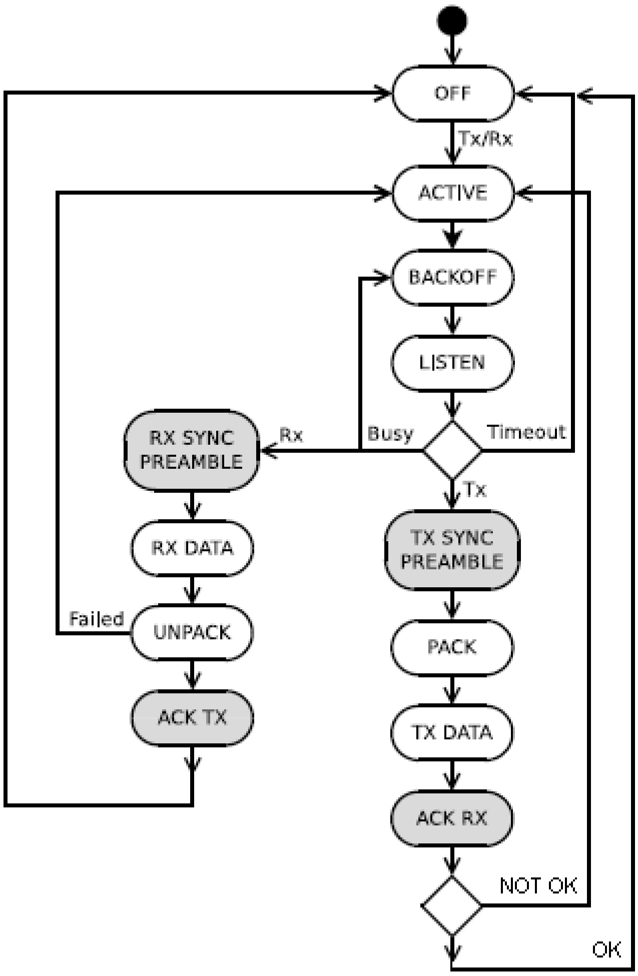

Figure 8-2 C-MAC Activity Diagram for B-MAC and RB-MAC. Highlighted states indicate which micro-components have different implementation. UNPACK has been used for error handling & security mechanisms

Figure 8-3 EPOSMote II SDK side-by-side with a R$1 coin. On the left the sensing module. On the right the main module.

We have configured C-MAC to mimic both B-MAC and RB-MAC and the probability *p* of a node successfully receive a packet was set to 1, 0.8, 0.5, and 0.3. To emulate the channel conditions in this implementation we have used the pseudo random algorithm provided by the operating system. Each time a node receives a packet it generates a random number. Within an interval, according to the generated random number and the probability *p* under test, the packet may be discarded.

Table 8-1 shows a comparison between the EPOSMote II specification with other popular wireless sensor nodes [CROSS], [MICA], [MICZ], [MC13].

Table 8-1 Comparison of different sensor specifications

Mote	TelosB	Mica2	MicaZ	EPOSMote II
MCU	MSP430	ATmega128L	ATmega128L	ARM7TDMI-S
Processor Speed	8 MHz	8 MHz	8 MHz	26 MHz
Program Flash Memory	48 K	128 K	128 K	128 K
RAM	10 K	4 K	4 K	96 K
Processor Current Draw - active mode	1.8 mA	8 mA	8 mA	3.3 mA
Processor Current Draw - sleep mode	5.1 μA	< 15 μA	< 15 μA	0.85 μA
Radio	CC2420	CC1000	CC2420	Integrated transceiver
Radio frequency	2400 to 2483.5 MHz	315/433/915 MHz	2400 to 2483.5 MHz	2405 to 2480 MHz
Rx Current Draw	21.8 mA	10 mA	21.8 mA	22 mA
Tx Current Draw	19.5 mA	27 mA	19.5 mA	29 mA

Figure 8-4 shows the evaluation scenario. At first, one node is set as sender and another one as receiver. Both BMAC and RB-MAC are evaluated for each probability *p*. When all probabilities are tested another receiver is added and this process repeats itself until the network possess a total of four receivers at the same time.

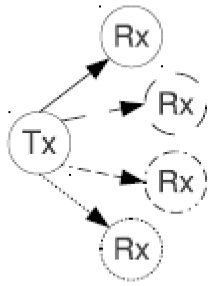

Figure 8-4 Evaluation scenario

Both protocols were evaluated in terms of memory used (footprint), latency and energy consumption. For all experiments, we have used: the GNU GCC compiler for ARM [ARM], version 4.4.4; the ARM processor clock was set to 24 MHz; CCA duration of 1.43 ms; preamble duration of 143.8 ms; data packets size of 94 bytes; and 4.5 dBm of transmission power. We have used the `arm-size` tool, from GNU Binutils version 2.20 [BINU], to obtain the memory footprint of both protocols. Results are shown in **Table 8-2**. It shows the data segment portion of virtual address space of a programme. ".text" represent the execution instructions, ",bss" represents the statically allocated variable. As expected, RB-MAC presents a larger footprint since it uses more complex mechanisms. While B-MAC uses dummy preamble content, RB-MAC uses helpful information allowing nodes to go back to sleep or even quit contention. In addition, B-MAC uses simple acknowledgement packets as transmission confirmation, while RB-MAC uses a contention window mechanism to check if a transmitted packet is being properly forwarded.

Table 8-2 Memory footprint (bytes)

Section	B-MAC	RB-MAC
.text	10780	11236
.data	38	38
.bss	5679	5679
TOTAL	16497	16953

In order to determine the time and amount of energy required to successfully transmit a packet for each protocol, we have used an oscilloscope as illustrated in **Figure 8-5**. A General Purpose Input / Output (GPIO) pin corresponding to a LED output pin in EPOSMote

II is connected to the oscilloscope and set to high before a transmission starts and reset to low right after the confirmation of reception.

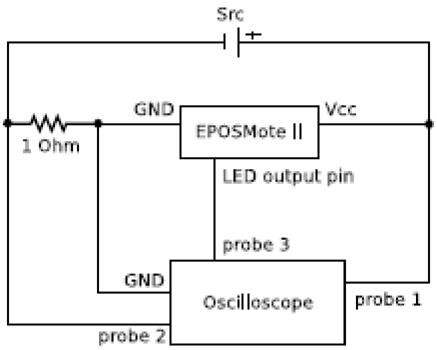

Figure 8-5 Schematic of the EPOSMote II connected to oscilloscope

Varying the channel conditions for both protocols, **Figure 8-6** presents the time taken to successfully transmit a packet, (including retransmission time). It is evident that B-MAC's performance in terms of delay deteriorates as the packet reception probability decreases and that it is not even influenced by the number of receiver nodes. This happens because, in B-MAC, the sender node sends the data to a specific receiver. Thus, the lower the probability of reception, the more retransmissions will occur, thereby increasing the necessary time to successfully transmit a packet. As for the RB-MAC protocol, the sender does not have a specific receiver, and all neighbouring nodes are potential receivers. The more neighbours, the greater the chance that a message will successfully be received. When the probability of packet reception is equal to one, there is no need for retransmission, and both protocols have the same behaviour.

The energy consumption to successfully transmit a packet, including retransmissions, is illustrated in **Figure 8-7**. Since a transmission in B-MAC has a specific receiver, other receivers in the network becomes synonymous to idle listeners, in other words, wasting energy. Furthermore, the lower the probability of reception result in the greater number of retransmissions and higher energy consumption. As for RB-MAC, more neighbours mean fewer retransmissions. Nevertheless, this does not always means less energy consumption. There is a relation between the probability of reception and the energy spent on unnecessary listening in which, after a certain point, adding a receptor does not reduce energy consumption. This happens because only one of the receivers has to get the data, so the energy consumed by other receivers is wasted. Therefore, when the energy consumed by other receivers is higher than the energy saved by reducing retransmissions, then the total energy consumption increases. This relation can be observed in Figure **8-7**. At the configuration RB-MAC with p = 0.5, the energy consumption reduces from one to two receivers, from two to three, but starts to increase with four receivers.

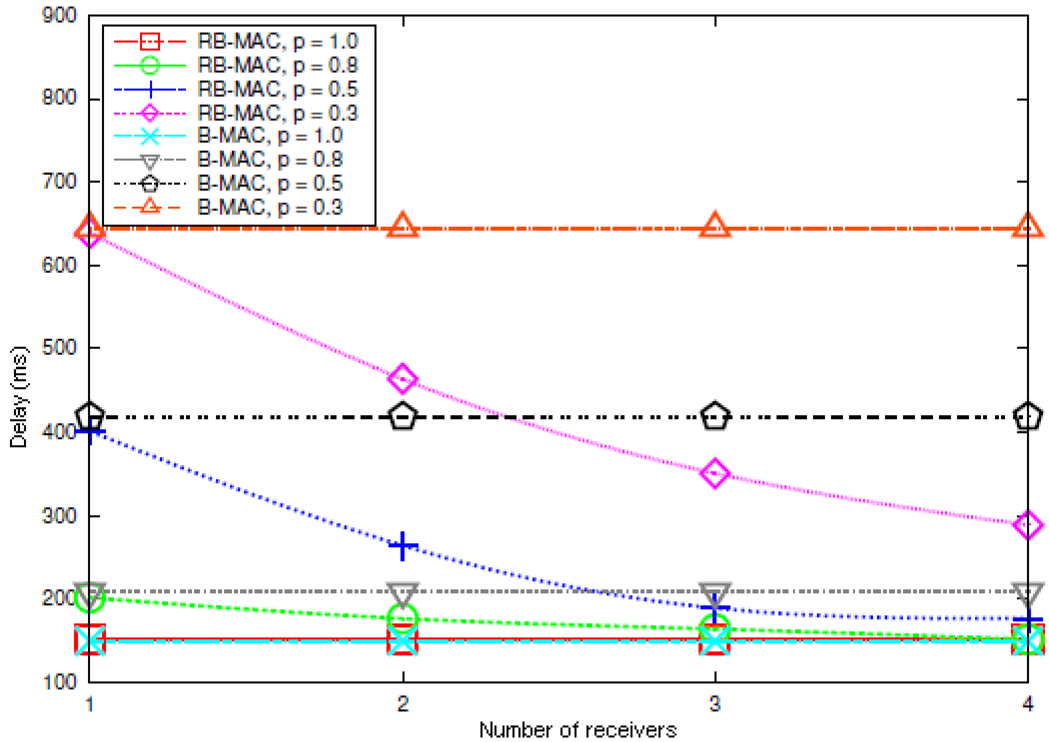

Figure 8-6 B-MAC and RB-MAC latency in varying channel conditions

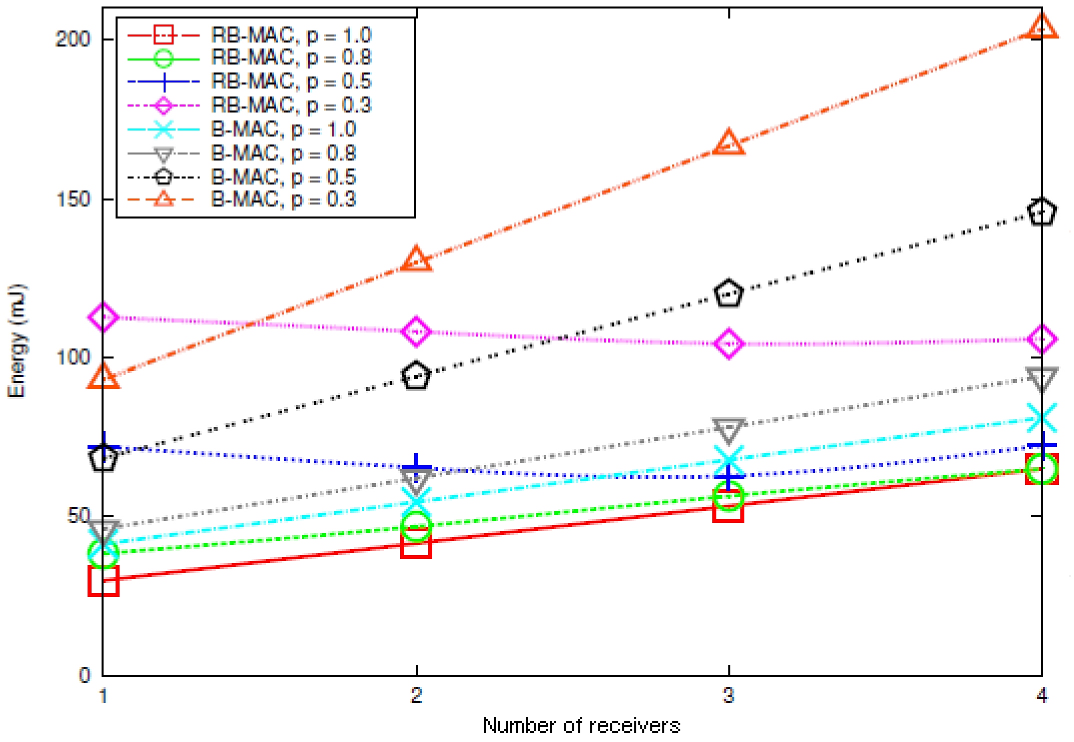

Figure 8-7 B-MAC and RB-MAC energy consumption in varying channel conditions

8.4. Conclusions

This chapter presented the performance evaluation of RB-MAC using real implementation. Using the C-MAC framework and real sensor nodes, the performance of RB-MAC was compared with B-MAC as a representative MAC for a sender-based protocol. The results indicate that as the channel quality degrades the number of retransmission increases in both RB-MAC and B-MAC. However; as number of network nodes increase, RB-MAC requires fewer retransmissions, consequently, reducing overall transmission delay and energy consumption whereas in B-MAC there is no relation between increasing the node degree and number of retransmissions. This is because B-MAC only relies on one particular sender node as a receiver and keeps retransmitting. The results confirm that RB-MAC outperforms B-MAC in terms of delay and energy consumption in lossy links.

9. Conclusions and Future Work

This thesis studied reliable and energy-efficient forwarding mechanisms in low-power and lossy wireless sensor networks, with a particular focus on adaptive receiver-based preamble sampling MAC and RPL routing protocol.

Generally, retransmissions are used to maintain reliability of data delivery. We have shown that retransmissions are not energy-efficient in low power and lossy WSNs due to high dynamicity of the network. We have proposed receiver-based preamble sampling MAC (RB-MAC) protocol which the next receiver is dynamically selected among potential neighbours, based on current channel conditions for energy-efficiency and reliability.

RB-MAC is based on preamble sampling. This state-of-the-art MAC technique achieves low power consumption in low-data rate networks by having nodes sample the channel in an unsynchronised way in a very low duty cycle. The resulting preamble sampling RB-MAC protocol, when a sensor node has a packet to send, broadcasts a preamble followed by data to all its neighbours without assigning a particular node as a receiver. All nodes within the communication range of the sender node receive the packet and compete to be the next forwarder. The probability of receiving the packet without error in multiple receiver setting is higher than that of having one receiver. This means that fewer retransmissions occur in lossy network and this translates to a reduction in energy consumption and delay as well as higher reliability for data delivery. Passive acknowledgment ensures at least one of the candidates forwards the packet.

Two versions of RB-MAC were proposed. as-MAC assumes adaptive sampling for sensor nodes. Based on this assumption, nodes with lower energy level (i.e. less remaining energy, or low energy-harvesting rate) choose larger checking interval (CI) and sample the channel less often than other nodes to save energy and give high-energy nodes more chance to win the competition. as-MAC dynamically selects the checking intervals in the nodes so as to reduce energy consumption in the nodes and network. In ap-MAC technique, sensor nodes can adapt their preamble size. By reducing preamble length, greater energy savings can be achieved in the sender nodes and the number of competing nodes in the forwarding process can be reduced. Using ap-MAC in dense networks or rather good channel conditions can result in reduced delay for data delivery and increased energy-efficiency while maintaining the same level of reliability.

Performance of RB-MAC and its variations was compared with sender-based MAC protocols using numerical, simulation runs and practical implementation. The results for single-hop scenario showed RB-MAC outperforms other sender-based MACs in energy-efficiency, reliability and delay for low power and lossy WSNs. We extended this to multi-hop scenario by applying ap-MAC, as-MAC and RB-MAC to IETF’s RPL routing protocol, which is specifically designed for low-power and lossy networks (LLN). We described how RB-MAC, two variations and RPL can be combined, forming an energy-efficient, communication architecture at layer 2 and 3.

The proof-of-concept practical experiment has shown the validity of RB-MAC. Using a configurable MAC framework in real sensor nodes, RB-MAC and sender-based MAC (B-MAC) were implemented. The results confirm that RB-MAC is significantly more resilient to lossy links when compared to B-MAC. As the number of network nodes increase, RB-MAC requires fewer retransmissions consequently reducing transmission delay and energy consumption.

We can explore the following as further work activities:

1. How adaptive RB-MAC can be used to deliver different classes of service such as:
    - Max-reliability: Guaranteed end-to-end reliability: for critical data
    - Min-energy: Data packets need to be delivered with minimal energy consumption; reliability and end-to-end delay are not the primary concern.
    - Min-delay: Critical data requires minimal end-to-end delay, without any considerations for energy efficiency.

- Deadline: Data needs to be delivered before a predefined deadline with minimal energy-consumption.

2. We can investigate the application of RB-MAC in smart-grid networks especially Advanced Metering Infrastructure (AMI) networks. The topology in these type of networks takes the form of a tree rooted at the gateway. The quality of wireless links is generally unstable due to fading and interference effects. Using RB-MAC, we can improve the reliability of AMI networks as well as optimise operation for specific service requirements.
3. In Cognitive Radio Ad Hoc Networks (CRAHNs) [Aky09], using opportunistic nature of RB-MAC, we can specifically design an integrated routing and MAC protocol for finding better paths. These paths can be tailored towards primary receiver protection or meeting QoS requirements of the secondary network.

Appendix I

Assume that the received Signal-to-Noise Ratio (SNR) at node l transmitted from a node k is given by $\gamma_{k,l} = \frac{P_{k,l}|h_{k,l}|^2}{\sigma^2}$, where $P_{k,l}$ is the transmission power of k^{th} node for transmission to the l^{th} node, $h_{k,l}$ is the channel coefficient between nodes k and l, and σ^2 denotes the power of AWGN. The channel coefficient, $h_{k,l}$ is given by $h_{k,l} = F_{k,l}\sqrt{1/Z_{k,l}}$, where $F_{k,l}$ represents the channel fading coefficient and $Z_{k,l}$ is the path loss. The channel fading coefficient, $F_{k,l}$, is modeled as independent circularly symmetric complex Gaussian distributed with zero mean and unit variance. Assuming a free space path loss model, the path loss between nodes k and l, is given by

$$Z_{k,l} = \left(\frac{4\pi}{\lambda}\right)^2 \left(\frac{1}{D_f^2}\right)^{\alpha} D_{k,l}^{\alpha}$$

where α is the path loss exponent, D_f is the reference distance for antenna far field, and $D_{k,l}$ is the distance between nodes k and l. The expected value of the channel power gain is given by

$$E\left\{|h_{k,l}|^2\right\} = \sigma_{k,l}^2 = 1/\xi D_{k,l}^{\alpha},$$

where $\xi = \left(\frac{4\pi}{\lambda}\right)^2 \left(\frac{1}{D_f^2}\right)^{\alpha}$. It follows that $|h_{k,l}|^2$ is exponentially distributed and the probability density function (PDF) is given by

$$f\left(|h_{k,l}|^2, \sigma_{k,l}^2\right) = \begin{cases} \frac{1}{\sigma_{k,l}^2}\exp\left(-\frac{|h_{k,l}|^2}{\sigma_{k,l}^2}\right) & |h_{k,l}|^2 \geq 0 \\ 0 & |h_{k,l}|^2 < 0 \end{cases}$$

Let $\Gamma_{k,l}$ be the outage threshold for the channel between nodes k and l and let Ψ indicate the probability of this outage and is given by

$$\Psi = Pr\left(\left|h_{k,l}\right|^2 < \Gamma_{k,l}\right)$$

Using the PDF of $\left|h_{k,l}\right|^2$ be the outage probability Ψ is given by

$$\Psi = 1 - \exp\left(-\frac{\Gamma_{k,l}}{\sigma_{k,l}^2}\right)$$

Assuming Ψ be a fixed system parameter, once can find $\Gamma_{k,l}$ by

$$\Gamma_{k,l} = -\sigma_{k,l}^2 \ln(1 - \Psi)$$

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